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RECENT AND FOSSIL RIPPLE-MARK

by

E. M. Kindle

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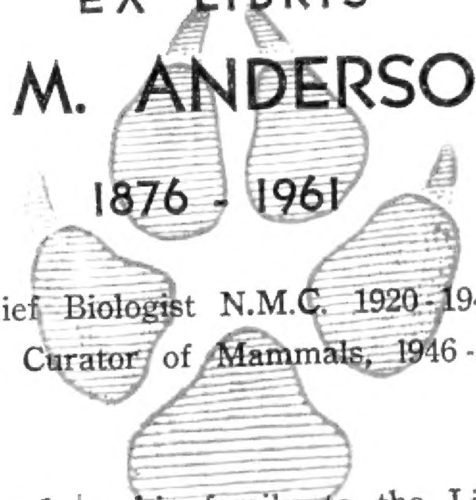

CONTENTS.

ILLUSTRATIONS.

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INTRODUCTION.

The general mechanical principles underlying the phenomena of ripple-mark formation have been made the subject of experimental laboratory investigations by various geologists,[1] who have developed the physical theory of this subject to a fairly satisfactory stage. The present study makes no attempt to enter this field but confines itself to the description and illustration of the phases of ripple-mark phenomena met with on sandy sediments and their correlation with the geologic agencies which produce them.[2]

The study of ripple-mark formation under present conditions was undertaken for the purpose of securing more precise conceptions of the significance of the different types of fossil ripple-mark. A definite and distinctive type of ripple-mark, always results from current action on sandy bottom, a different type

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[1] Hunt, A. R., "On the formation of ripple-mark," Proc. Roy. Soc., London, vol. XXXIV, 1882, pp. 2-18.

de Candolle, C., "Rides formées à la surface du sable déposé au fond de l'eau et autres phénomènes analogues," Archives des sciences physiques et naturelles, Geneva, 3e sér., IX, 1883, pp. 241-278.

Forel, F. A., "Les rides de fond étudiées dans le lac Léman," Archives des sciences physiques et naturelles, 3e sér. X, 1883, pp. 39-72.

Darwin, G. H., "On the formation of ripple-mark in sand," Proc. Roy. Soc., London, vol. XXXVI, 1883, pp. 18-43.

Cornish, Vaughan, "On the formation of sand-dunes," Geog. Jour., vol. IX, 1897, pp. 278–309, figs. 1–25.

H. Ayrton, "The origin and growth of ripple-mark," Proc. Roy. Soc., ser. A, vol. 84, 1910, pp. 285–310, figs. 1–15, plates 3–4.

[2] An excellent summary accompanied by bibliographic references to much of the literature on ripple-mark, by Prof. D. W. Johnson, appeared after this paper was completed; to which the reader is referred—"Contributions to the study of ripple-marks," Jour. Geol., vol. 24, 1916, pp. 809-819.

from wave action, and still another type from the direct action of the wind on sand. If these different types can be recognized by the geologist in examples of fossil ripple-mark, their discrimination will in many cases afford important aid in determining the history of the formations with which he has to deal. Marine deposits of the coastal zone are subject almost continuously during their formation to the action of tidal currents; while in the formation of lake deposits the influence of such currents is absent and the presence of other currents is comparatively rare. The preponderance, therefore, in a given formation of the wave-made type of ripple-mark, would furnish strong evidence of continental origin. The general occurrence on the other hand of current made ripple-mark and absence of the wave type would afford very strong evidence of marine origin.

The present paper aims to present the criteria by which the many varieties of ripple-mark met with in nature may be referred to a few general types. These distinctive characteristics are shown chiefly through the use of photographs and profiles from casts of plaster of paris moulds taken directly from ripple-mark shortly after its formation and from fossil ripple-mark. The conditions under which the recent ripple-mark thus illustrated has been formed have in most cases been carefully observed. Many of the moulds have been taken under water by means of specially devised apparatus.

A distinct relationship exists between the physical geography of modern seas, lakes, and estuaries and the currents and waves within them. Currents and waves so impress themselves on the deposits formed under their influence that their characters may be recognized from the peculiarities of these deposits. Hence through the correct interpretation of the physical features of ancient sediments in terms of the current and wave factors which moulded them, the features of the attendant physical geography can be inferred within certain limits.

Geological literature abounds with references to ripple-mark which indicate a lack of knowledge of the different types of ripple-mark and of the varying conditions under which they are produced. In a paper published recently the surprising statement is made that "ripple-marks are the work of the tide and of that alone."[1] Various authors, who evidently are not aware that certain types of ripple-mark may be formed at great depths, speak of fossil ripple-mark as an evidence of shore or very shallow water conditions. Geologists are also told that observation of fossil ripple-mark affords in areas of great orogenic disturbance a means of determining whether the beds have been overturned or not, without being told what types can and what can not be used in this way. These and other considerations have led to the belief that a detailed discussion of the conditions under which ripple-mark is formed in nature would be useful to geologists. This belief appears to be well supported by one of the ablest investigators of ripple-mark who wrote as late as 1904 that "The apparent contradictions of writers on ripple-mark are so surprising that one fails to see how the student or even the text-book writer can find his way through the mist."[2]

Consideration of ripple-mark on calcareous beds will be omitted from this discussion because the writer has had no opportunity to study its formation on recent deposits.

RECENT RIPPLE-MARK.

GENERAL CONSIDERATIONS.

Beds of sand when exposed either to wave action or to currents of air or water of the proper degree of intensity, become covered by the beautiful flutings known as ripple-marks. On the sea beach at low tide the sandy strectches, with their innumerable, equally spaced ridges and furrows look as if they might have been combed with a giant comb. The parallelism of the troughs and ridges of ripple-mark distinguish it from other forms of water sculpture (Plate VII). Wherever beds of sand occur which are subject to the action of subaqueous or subaerial currents with neither too low nor too high a velocity, or to wave action, ripple-mark is formed. Material in which there is little or no cohesion between the particles composing it is essential to ripple-mark formation. Mud, marl, and slimy sediments are never ripple-marked. It sometimes happens that a bed of mud and sand is

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[1] Ann. Rept. Smith. Inst., 1913 (1914), p. 310.

[2] Hunt, A. R., Nomenclature of ripple-mark, Geol. Mag., vol. I, p. 417, 1904.

separated by a sharply defined contact line; in such a case ripple-mark if present on the sand will stop abruptly at the mud contact line. I have observed striking examples of this truncation of ripple-mark pattern by mud beds along the St. Lawrence river. The limitation of ripple-mark to granular sediments affords an important clue to the original texture of ripple-marked limestones.

The universality of this phenomenon on the sands of dune and desert regions and on the sandy beds of seas, lakes, and rivers, gives to it a degree of importance hardly suggested by the brief treatment usually accorded to it in textbooks. Ripple-mark, as observed by Sir J. D. Hooker,[1] has sometimes been mistaken for the fluting of Sigillaria stems and has led to the grave error of determining as Coal Measures beds far removed from this horizon.

A record of the work of air and water currents has been inscribed in terms of ripple-mark on some of the oldest of the sedimentary rocks. Even before marine life began to record its history with fossil remains, ripple-mark was being formed which has persisted in a good state of preservation to the present time. In many later formations where fossils are rare or unknown ripple-mark is often most beautifully preserved. Thus it happens that where the palæontological record fails much may be gleaned from a study of ripple-mark concerning the history of older sediments. Fossil ripple-mark should indicate whether the material impressed by it was laid down under wave or current action, and if currents were present their direction and within certain limits their velocity. Where both fossils and ripple-mark are preserved in the same beds the correct interpretation of the latter may aid greatly in understanding the environmental conditions of the former. It is evident that any trustworthy interpretation of the significance of fossil ripple-marks must rest upon a detailed study of the conditions under which they are now being formed. The first part of this paper will, therefore, undertake to indicate the conditions under which the several types of ripple-mark are formed. With reference to their

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[1] Himalayan Journals, pp. 31 and 41, 1891.

modes of formation ripple-mark may be classified as current ripple-mark, wave ripple-mark, and ripple-mark resulting from combinations of these two fundamental types. Dune ripple-mark is the product of air currents and belongs in the first mentioned class. This subaerial form of ripple-mark is distinguished by well marked features from subaqueous ripple-mark.

FIELD WORK AND METHODS.

Parts of three field seasons have been devoted to the accumulation of the data on which this paper is based. The field observations have been made chiefly along the shores of lakes Ontario, Erie, and Deschenes, and the bay of Fundy. A few days were also spent in studying ripple-mark phenomena along the St. Lawrence river between Montreal and lake St. Peter. Through the courtesy of Mr. H. L. Cole of the Mines Branch, I had the use, during the St. Lawrence River studies, of quarters on a launch which had been chartered for the purpose of investigating, from the economic standpoint, the sand deposits along the St. Lawrence river. Much of the field work has been taken up for periods of a few days or weeks when expeditions planned primarily for researches in stratigraphic palæontology have made easily accessible areas favourable for ripple-mark studies.

In both field and office work, E. J. Whittaker has furnished invaluable assistance.

A primary object of the field work has been to get a precise knowledge of the shape and physical features of ripple-mark as it exists under water where it is formed, and of the special conditions under which different types are developed. Such information concerning bottom features as the observer can obtain by looking through the water from a boat is subject to the same limitations as are his observations of fish and other forms of subaqueous life. The naturalist fortunately has his dredge but it affords no aid in the study of ripple-mark. I have, however, found it possible by means of plaster of paris to secure perfect moulds of ripple-mark in which the finest details of contour are preserved without the slightest distortion or compression. By this means exact duplicates in plaster of the various types of ripple-mark which occur on lake, stream, and sea bottom have been obtained for office study, and comparison with a considerable collection of fossil ripple-mark. The collections which have been acquired during the progress of the work include a fine slab of ripple-marked Berea sandstone from Ohio which was presented to the Museum by Prof. C. S. Prosser, and specimens of Cambrian sandstone ripple-mark from northern New York collected and presented by Mrs. Orra P. Phelps. I am also indebted to Mrs. Phelps for valuable photographs and profiles of Cambrian ripple-mark. Several members of the Geological Survey have contributed interesting specimens of fossil ripple-mark to this collection. The most important part of my own collection of fossil ripple-mark was secured at the Joggins section of the Nova Scotia coal measures. The plates of ripple-mark profiles in this paper and many of the photographs have been made from the plaster of paris duplicates of recently formed ripple-mark which have been made during the progress of the field work.

Where the water over the ripple-mark is very shallow—one foot or less—the process of taking a mould is very simple. Any box of convenient size may be used for the mould by knocking out the bottom and cutting the edges which are to be pressed into the ripple-marked sand to a bevel edge in order to produce the minimum disturbance of the beds. A size 10 by 16 or 18 inches has been found convenient to use. After pressing the edges of the wooden frame firmly into the sand on which the ripple-mark to be moulded is impressed, plaster of paris is sifted through a wire screen until a thickness of one inch or more of the plaster has been deposited inside the frame. Ripple-mark with deep furrows and angular crests, of course, require a thicker deposit of the plaster than the shallow trough type of ripple-mark. About one hour is required for the plaster to harden under water sufficiently to permit removal. Plaster moulds may be made from ripple-mark uncovered at ebb tide by using the wooden frame described above. Plaster of paris is sifted over the ripple-mark to be moulded inside the frame until a layer of the desired thickness has been spread over it. Water is then added by sprinkling very gently and uniformly until the entire upper surface is uniformly saturated, when it may be added more rapidly until the plaster is soaked throughout.

Moulds made in this way require a much shorter time to harden than when made under water.

For making moulds under water too deep to use the wooden frame referred to above I have devised a piece of apparatus comprising a base about 16 inches in diameter resembling an inverted dish-pan with a sharp edge, in which the plaster mould is formed. A cylindrical tin reservoir holding about $2\frac{1}{2}$ quarts is mounted on top of the broad circular base with which it is connected by a wide short neck at the bottom. This neck fits snugly into a hole in the centre of the base and is filled with a valve opening upward. The top of the reservoir is closed by a cap like that of a milk can. A small hole in the centre of this cap permits a string to pass which is connected with the valve at the bottom of the reservoir, thus permitting the operator to open the valve after the apparatus is in position for taking a mould on the bottom. Two or more valves in the top of the lower section of the apparatus so constructed as to open in descending and automatically close on reaching bottom facilitate the process of lowering to the bottom. Short nails inserted through holes in the lower margin of the apparatus prevent the mould from slipping out when the apparatus is lifted. The reservoir is filled with a mixture of plaster of paris and water, equal volumes of each being used; after reaching bottom the valve at the bottom of the reservoir is opened by means of the attached cord and the plaster of paris mixture pours into the base of the apparatus and forms the desired mould. It is necessary to empty the reservoir within five or six minutes after preparing the mixture since it becomes viscid in six or eight minutes. During the hour required for the setting of the plaster the apparatus is left marked by a buoy. In using either this or the ripple-mark mould apparatus the operator should be provided with a small instrument known as a "telegraph snapper" for sampling the bottom and locating sandy deposits in which ripple-mark may be expected. Another desirable but more expensive piece of apparatus which can be used advantageously in studying current ripple-mark is the Ekman current metre. This instrument records not only the velocity but the direction of the current as well. It, therefore, enables the investigator when dealing with current ripple-mark to determine the orientation of the ripple ridges and troughs whatever the depth may be. The very brief period during which the plaster mixture remains fluid after preparation limits the depth at which this method is practicable.

Another device usable at any depth, which I have employed in obtaining information regarding the spacing or amplitude of ripple-mark in water too deep for taking ripple-mark moulds, consists of a thin piece of sheet iron or zinc 18 or 20 inches square. A hole at each corner affords a means of attaching four short cords to the metal plate; these are united to a single cord by which the plate is lowered after being properly weighted. The under side of the plate is coated with vaseline. When drawn up the plate will show parallel lines of sand corresponding to ripple-mark crests, if ripple-mark has been encountered.

WIND RIPPLE-MARK.

The ease with which every feature connected with the development of wind-made ripple-mark can be observed, makes it convenient to begin the study of ripple-mark with the examination of this type of ripple-mark which finds its best development on the surface of sand dunes (Plates I and II).

Sir Chas. Lyell's[1] description of the formation of ripple-mark by the wind can hardly be improved upon as regards the essential facts which are stated thus by him:

"The following is the manner in which I once observed the motion of the air to produce this effect (ripple-mark) on a large extent of level beach, exposed at low tide near Calais. Clouds of fine white sand were blown from the neighbouring dunes, so as to cover the shore, and whiten a dark level surface of sandy mud, and this fresh covering of sand was beautifully rippled. On levelling all the small ridges and furrows of this ripple-mark over an area several yards square, I saw them perfectly restored in about ten minutes, the general direction of the ridges being always at right angles to that of the wind. The restoration began by the appearance here and there of small detached heaps

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[1] Elements of geology, 6th Ed., 1841, pp. 41-43.

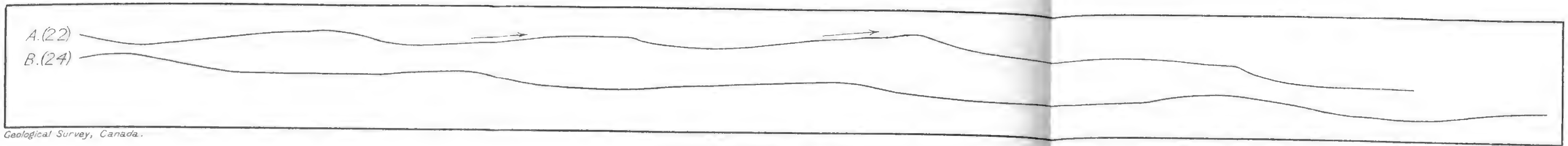

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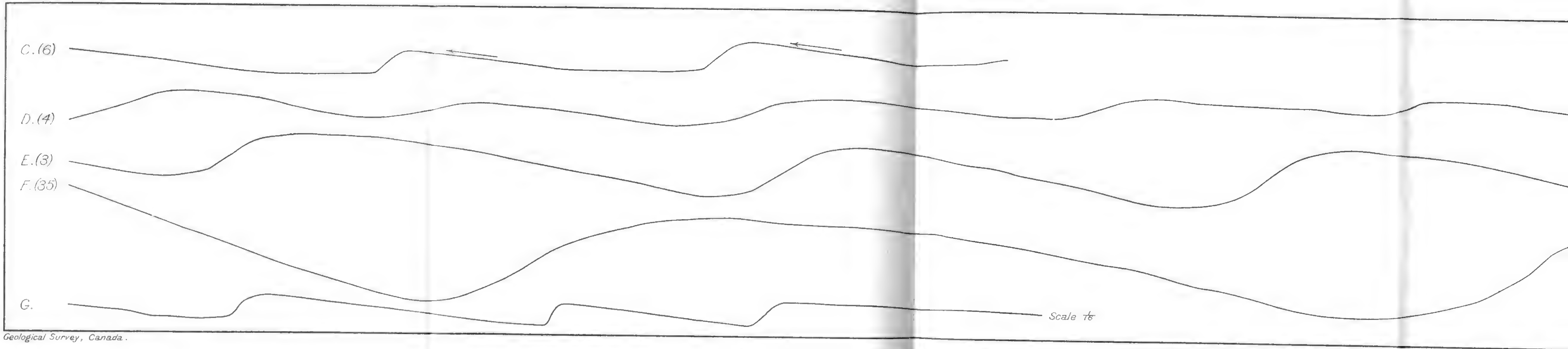
Fig. 2 — **Wind ripple-mark** profiles (x1.)
A From beach at Pt Colborne, Ont.
B From cast shown in photograph pl. 2, **A.**



Geological Survey, Canada.

Fig. 3 — Asymmetrical **current ripple-mark** profiles (x1. except G)
C. From cast of ripple-mark on muddy sand shown pl. 10, **B.** Arrow indicates relation of this and succeeding profiles to current.
D.E.F.G. Profiles resulting from tidal currents showing amplitude varying from 3 inches to 4 feet. E from cast shown in pl. 9, **B.** G from cast shown in pl. 8, **A.**

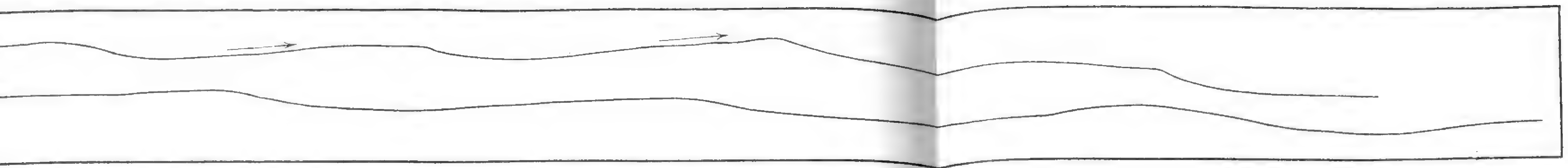


Fig. 2 – **Wind ripple-mark** profiles (x1.)

A From beach at Pt Colborne, Ont.

B From cast shown in photograph pl. 2, **A.**

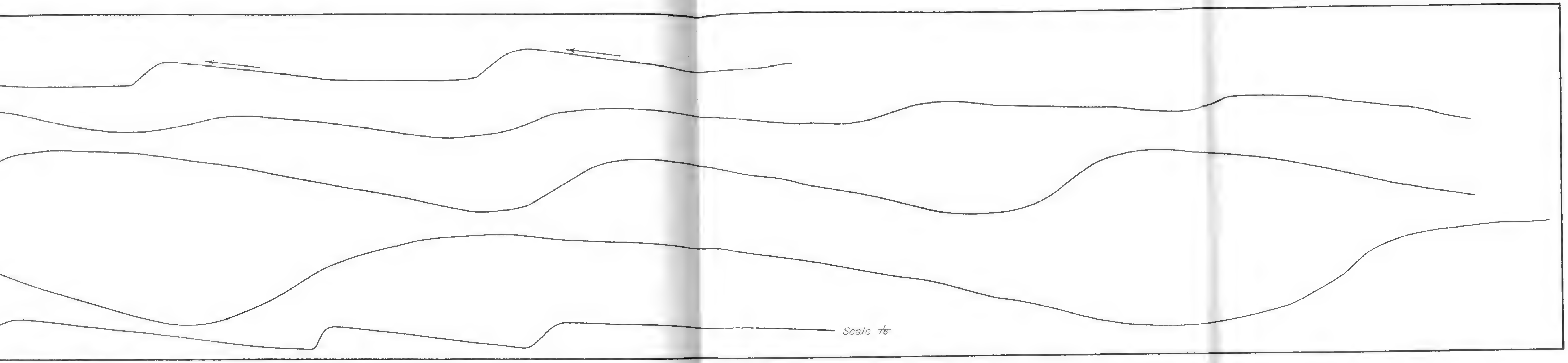


Fig. 3 – Asymmetrical **current ripple-mark** profiles (x1. except G)

C. From cast of ripple-mark on muddy sand shown pl. 10, **B.** . Arrow indicates relation of this and succeeding profiles to current.

D, E, F, G. Profiles resulting from tidal currents showing amplitude varying from 3 inches to 4 feet. E from cast shown in pl. 9, **B.** G from cast shown in pl. 8, **A.**

of sand, which soon lengthened and joined together, so as to form long sinuous ridges with intervening furrows (Figure 1). Each ridge had one side slightly inclined, and the other steep; the lee-side being always steep, as bc and de; the windward-side a gentle slope, as ab and cd. When a gust of wind blew with sufficient force to drive along a cloud of sand, all the ridges were seen to be in motion at once, each encroaching on the furrow before it, and in the course of a few minutes filling the place which the furrows had occupied. The mode of advance was by the continual drifting of grains of sand up the slope ab and cd, many of which grains, when they arrived at b and d, fell over the scarps bc and de, and were under shelter from the wind; so that they remained stationary, resting, according to their shape and momentum, on different parts of the descent, and a few only rolling to the bottom. In this manner each ridge was distinctly seen to move slowly on as often as the force of the wind augmented."

Figure 1. Wind ripple-mark, profile after Lyell.

The diagrammatic figure here reproduced after Lyell, although the troughs are too deep for their width, very well illustrates the mode of formation and movement of ripple-mark. The lee slope is much longer in proportion to the windward slope than it is ever found in nature. The actual relations and appearance of the lee and windward slopes in wind ripple-mark are shown in Figure 2A and B. These show the very short lee slope and shallow trough which are characteristic of wind ripple-mark.

Examination of a large number of sand dunes along the north shores of lakes Ontario and Erie shows the surface of the sand, where free from vegetation, to be nearly everywhere covered by ripple-mark in dry weather (Plate I). These, of course, are obliterated by heavy rains but reappear soon after the surface dries. The only areas which are free from the ripple-marks are those where the slope is very steep, and where the action of the wind is interrupted by trees or other obstructions. Whenever the wind is strong enough and the surface of the dune sufficiently dry for sand grains to roll freely the whole surface of a sand dune to a depth equal to the elevation of the ripple-mark crest above its trough moves forward through the progressive movement of the hundreds or thousands of ripple-marks which cover it. The rate of movement of the ripple-mark depends on the size of the grains and the velocity of the wind. Observations on the dune sand east of Wellington showed the ripple-mark during a gentle breeze to be advancing with it at the rate of 4½ inches per hour. At Port Colborne on lake Erie measurement of the movement of wind ripple-marks made in connexion with anemometer readings showed the ripple-mark to be moving at the rate of 24 inches per hour with a wind velocity of 12·9 miles per hour. This ripple-mark had an amplitude of 3½ to 5 inches with a depth of about ⅛ inch.

The size or amplitude of wind ripple-mark varies but little with variation of wind velocity. The variations in amplitude noted in measuring some hundreds of examples on the dunes near Wellington all fell between 2 and 4 inches. The height of the crest above the trough in all of these was very close to ⅛ inch. Although variation of wind velocity appears not to affect the amplitude of the ripple-mark its rate of advance is directly proportional to it. My observations with reference to the slight variation in the amplitude of sand ripple-mark within the limits of an area of the same degree of fineness of sand grains coincide with those of W. W. Strickland who states that "The first thing to be observed about them is that they are nearly all the same size, viz., about 3½ inches from crest to crest."[1]

W. Harding King[2] who has studied dune ripple-mark in desert regions writes: "So far as I have seen the ordinary rippling on a dune never develops much beyond 4 inches in average length."

The principal factor controlling the slight amount of variation which is shown by the amplitude, appears to be the coarseness of the sand. The crests of wind ripple-mark at Sand Banks on lake Ontario were found to be separated by intervals of from 2 to 4 inches.

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[1] "Notes and observations on forms of sand," pp. 1-36, 32 figs., 1915, p. 16: R. H. Smithson and Blanchard, London.

[2] W. J. Harding King, "The nature and formation of sand ripples and dunes," Geog. Jour., vol. XLVII, 1916, p. 191.

At Port Colborne on lake Erie, with the exception mentioned below, they varied in amplitude between 3½ and 5 inches. The sand at the latter point is slightly coarser than at Sand Banks. A wind gap about 80 yards wide and 60 feet deep has been cut across the sand ridge which borders the north shore of lake Erie one-half mile west of Sugar Loaf sand dune. Near the lake end of this wind gap the sorting action of the wind has left some very coarse sand on the lower part of an up-slope. Wind ripple-mark of a very rude type was observed on this coarse sand. The ridges were quite irregular in their trend as well as parallelism. The troughs were about 10 inches apart and one-third inch in depth. These observations appear to show that the amplitude increases with the coarseness of the sand. This was the conclusion reached by Sokolow[1] who found that the height and amplitude of the ripples vary with the size of the sand grains.

In the case of very coarse sand ordinary wind velocities either produce no ripple-marks or very irregular ones. Occasionally when both coarse and fine sand are present, examples of ripple-mark may be observed in which the coarse sand or fine gravel grains occupy the crests of the ripple-mark while fine sand comprises the slopes. Ordinarily, however, no distinction in the coarseness of the material of the slopes and the crests can be recognized in the lake Ontario and lake Erie dunes.

A unique variety of ripple-mark formed on highway dust by artillery fire so directed that the shells from the guns passed at a slight elevation above the road has recently been described.[2] The ripple ridges are reported to be one-half inch apart, much closer than they are ever formed in sand. They were produced according to the observer by the explosive wave passing over the road during the action of the field guns.

The most striking characteristic of wind-made ripple-mark is the very slight elevation of the ridges as compared with the height of the crests of ripple-mark made under water (Figures 2 and 3). This difference is clearly shown by a comparison of the ratios

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[1] Die Dünnen, Bildung, Entwickelung und Innerer Bau. Deutsche vom Verfasser Ergänzte Ausgabe von Andreas Arzreni, Berlin.

[2] The formation of dust-ripples by H.U.G. (C.F.), Nature, vol. 97, p. 530, 1916.

of the depth and width of troughs in wind-made and water-formed ripple-marks. This will be called the ripple-mark index.

The index numbers of two examples of water-made ripple-mark found respectively in the St. Lawrence river and lake Ontario, and determined from moulds, are 6·3 and 4. The index numbers of two examples of moulds of wind-made ripple-marks taken at Wellington are 24 and 25, thus showing an index number four to six times greater than that of the water-made ripple-marks. The sharp contrast in the height of the crest in dune ripples and in subaqueous ripples is illustrated by the profiles of examples of both types which have about the same amplitude as shown in Figures 2A and 4E.

ASYMMETRICAL RIPPLE-MARK.

The action of a current of water flowing over a bed of sand resembles closely in its effects the work of air currents on sand (Plate III A). The surface becomes covered with ripple-mark ridges and troughs which are asymmetrical like those produced by the wind on sand dunes (Plate VII A and B). Wherever tidal currents or river currents traverse beds of sand such ripple-mark is found in abundance. The asymmetrical or current ripple-mark is characteristic of marine and fluvial deposits but it is seldom met with in lacustrine sediments. The ridges trend at right angles to the direction of the current. The upstream slope is long and gentle while the downstream slope is short and steep (Figure 3C-G and Plates VII and X to XII). Like the wind-ripples they travel with the water current which is continuously eroding the upstream side of the ripple-mark ridges and carrying the grains over the crest and dropping them in the trough. The obstruction to the current caused by the ridge of the ripple-mark creates an eddy in the lee of the crest and the return current of this vortex keeps a film of sand grains ascending the lee side of the ripple-mark against the general current thus preventing the troughs from filling, while ripple-ridges move forward with the current. Under the action of a strong current this movement is comparatively rapid. Where the current is barely perceptible and too weak to initiate ripple-mark it will still be able to slightly modify the shape of wave-made ripple-mark as it is developed and to cause it to migrate so long as wave action is active. Two cases were observed and timed near Lanoraie on the St. Lawrence by placing pegs in the ripple crests. In one case ripple-mark ridges with an amplitude of $1\frac{1}{2}$ inches in 3 inches of water moved $1\frac{1}{2}$ inches in 20 minutes, a distance equal to their amplitude. In the other observation at the same locality ripple-marks with an amplitude of 2 inches in 6 inches of water moved 2 inches in 20 minutes. This ripple-mark was made by onshore waves working in the presence of a barely perceptible current. Many clear rivers with broad shallow streams and sandy bottoms afford good examples of current ripple-mark. In such streams the ripple-mark trends across the channel at right angles to the current and moves down stream when the current is sufficiently strong. In clear shallow streams the sharp crested parallel lines of ripple-mark may often be seen extending from bank to bank. The ripple-mark produced by river currents and that formed by tidal currents are both asymmetrical and easily distinguished from the symmetric type produced by wave action. The photographs reproduced in Plate IV A and B show a small brook flowing over a bed of sand near Ottawa. In this case the volume and velocity of the water was sufficient to develop ripple-mark only over the middle portion of the channel where the stream had its maximum velocity and depth. In this middle zone the photograph shows the water breaking into tongue-shaped ripples which are directly over corresponding ridges in the sand.

There is, according to Vaughan Cornish, remarkable exception to the usual downstream migration of current ripple-mark in the case of currents maintaining a velocity of about 2·2 feet per second. Cornish states that "The most remarkable property of the sand waves produced in very shallow water when the velocity attains about 2·2 feet per second is that they travel up-stream." . . . . "It is very curious to see a group of these sand ripples moving in procession up-stream against the current which produces them."[1] This phase of ripple-mark

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[1] "Waves of sand and snow," 1914, p. 278, F. Fisher Unwin, London.

behaviour has been mentioned by John S. Owens[1] and by G. K. Gilbert.[2] These ripple-mark ridges which travel against the current are called by Gilbert antidunes, the ordinary current ripples which travel with the current being called dunes by him. Gilbert recognizes three phases in connexion with the conditions governing migrating ripple-mark depending on the stream load. "With any progressive change of conditions tending to increase the load the dunes eventually disappear and the debris surface becomes smooth. The smooth phase is in turn succeeded by a second rythmic phase in which a system of hills travel upstream. These are called antidunes, and this movement is accomplished by erosion on the downstream face and deposition on the upstream face."[3] The term sand wave has been used frequently in Great Britain for the migrating ripple-mark, particularly when it is of large size. Some French writers have employed the term greve but I prefer the term asymmetrical or current ripple-mark. One American author[4] has used the terms "ripples of deposition" and "ripples of erosion" corresponding respectively to asymmetrical and symmetrical ripple-mark as these terms are used in this paper. This nomenclature is based upon inferences regarding the respective roles played by the two types of ripple-mark which are open to the question and is, therefore unsatisfactory. When viewed through water the symmetrical and asymmetrical types often can be distinguished only with difficulty or not at all. Because of their close resemblance the term ripple-mark should, I think, continue to be associated with the two types of fluting produced respectively by current and wave-action.

Reference may be made here to a recent paper by Ch. Epry[5] which introduces an explanation of the formation of ripple-marks wholly novel and different from the one generally accepted. No reference is deemed necessary by this author

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[1] London, Geog. Jour., vol. 31, 1908, p. 424.

[2] "The transportation of debris by running water," U. S. Geol. Surv., Prof. paper 86, 1914, p. 31.

[3] Ibid, p. 11.

[4] Brown, A. P., "The formation of ripple-marks, tracks, and trails," Proc. Assoc. Nat. Sc., Philadelphia, LXIII (1911), pp. 536-47.

[5] "Annales de l'Institut Oceanographique" (Fondation Albert 1er Prince de Monaco) Paris, vol. 4, pt. 3, 1912, Ann. Rept. Smithsonian Inst. for 1913 (1904), pp. 307-318.

to the excellent experimental work of Hunt, Darwin, and others which was designed to develop the principles underlying the formation of ripple-marks; but we are assured on the first page that "no one seems until now, to have definitely ascertained their cause." This author denies that wind and waves have any power to produce ripple-mark and states that "Ripple-marks are the work of the tide and of that alone." He concludes that ripple-marks are the product not of the direct action of the tidal current but of transverse currents which are accessory or incidental to the action of the tidal current with which they are associated. It is indeed surprising that he should forget that ripple-marks are formed on the bottoms of all small lakes with sandy beaches where tidal action is entirely absent and where wind developed waves are alone competent to produce them. The evidence furnished by the ripple-mark of any small lake directly controverts Dr. Epry's statement that "There is no correlation between the movements of the aerial ocean and the wrinkling of the sandy surface submerged under a very thin stratum of water......" One of the essential premises on which this new theory of ripple-mark formation is based rests on the author's observation that "On the upper beach ripple-marks are never found. They occur in contrast in great abundance on the lower beach...." With this observation as a starting point the author develops his theory that ripple-mark results from the interaction of the down-flowing currents of the upper steeper beach and the normal current of the lower less steeply graded beach meeting more or less at right angles to each other. It must be pointed out here, however, that this fundamental premise regarding the absence of ripple-mark from the upper beach is true only locally. I have observed on the uppermost part of the beach at Kingsport, N.S., perfectly developed ripple-mark where the beach is almost flat, so that no transverse current, such as Epry's theory calls for, could have been developed. Epry's statement that ripple-mark occurs only on the lower beach, though subject to numerous exceptions, is true for shores with a moderate tidal current; because during the first part of the ebb the direct current is too weak to produce ripple-mark. It is only on those parts of the beach which are uncovered after the ebb tidal current has reached approximately its maximum strength, that ripple-mark is generally abundantly developed. Some of the illustrations of ripple-mark parallel with the shore and the general trend of the tidal current (Figure 9[1]) which are introduced to prove his theory are undoubtedly chiefly the product of wave action and cannot be admitted to furnish any evidence of the work of supposed transverse currents. In brief this author entirely overlooks the fact that asymmetrical ripple-mark can be produced in any properly equipped laboratory by the direct action of a water current, or may be seen on the bed of any stream with suitable bottom, and that these will be oriented at right angles to the current. Symmetrical ripple-mark can likewise be developed by wave action under laboratory conditions. Comparison of Figures 3 C and 4 A and Plates VII and XXI will show the sharp contrast between these two types which have been confused by Epry.

Under the simple conditions existing in the bed of a shallow stream flowing over fine sand quantitative studies of the factors determining ripple-mark formation by current action have been made by two or three careful observers. Sowerby,[2] as a result of a study of the work of a small brook flowing over sand, has recorded the following observations regarding the relations between current velocity and ripple-mark formation:

"By these experiments, and by observations made in a clear brook at Fulwood (near Sheffield), I came to the conclusion that, when the velocity of the current is about 6 inches per second, sand with grains about a hundredth of an inch in diameter is drifted along slowly, and a surface is produced, grained in the line of the current, but no ripple-marks are formed. When the velocity is somewhat greater than 6 inches per second, ripples are produced. When it is about 1 foot per second, these are well developed and advance about 3 inches per minute, by the sand being washed up on the exposed side and deposited on the other; which velocity may be looked upon provisionally as an average for undoubted drifted ripples. If the velocity attains 18 inches per second the ripples are destroyed by the washing away of the

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[1] Of Epry.

[2] Henry C. Sowerby, "On the application of quantitative methods to the study of the structure and history of rocks," Jour. Geol. Soc., vol. LXIV, 1908, p. 180.

sand; but the surface may still show graining in the line of the current. Much depends, however, on whether sand is or is not being deposited from above; since, when it is, ripples are produced at a somewhat lower velocity and advance more quickly. These results applied to the case of water varying from 1 to 8 inches in depth, and might be very different in the case of much deeper water. I have long felt that such experiments ought to be conducted on a much larger scale but had never had the opportunity in a suitable and convenient place, free from disturbance. In the present state of the subject it may be assumed that, in the case of moderately fine sand, the well-developed ripple-drift, so common in certain rocks, indicates a current with a mean velocity of about 1 foot per second." Owen[1] has also investigated the relations which exist between ripple-mark formation and current velocity. That portion of his table relating to ripple-mark follows:

Nature of bottom.	Depth in inches.	Velocity of current.	
		Miles per hour.	Feet per second.
Rippled sand....................	1	0·91	1·33
Rippled sand....................	2	0·92	1·35
Rippled sand, soft................	3	1·20	1·76
Rippled sand, very soft...........	5	1·50	2·20
Fine sand moving in a sheet, not rippled....................	3½	1·70	2·50
Sand moving in a sheet, not rippled	3	1·84	2·7
Sand moving in a sheet, no ripples.	3	2·18	3·20

A favourable locality for observing the correlation of current velocity with the formation or non-formation of ripple-mark was found in the Avon river a half mile above the railway bridge at Windsor, Nova Scotia. There at low tide a section of the river about 125 feet long by 45 feet wide flows over a stretch of sand with very uniform slope but with sufficient grade to give a strong current; a good opportunity is afforded to observe the successive formation of a series of ripple-mark

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[1] "Experiments on the transporting power of sea currents," Geog. Jour., vol. XXXI, 1908, pp. 415-420.

ridges and their destruction by the automatic variation of the current velocity above and below the critical velocity for ripple-mark formation. In the first stage of the cycle of ripple-mark formation observed, a strong current flows over a smooth unrippled sheet of sand; then ripple ridges form extending across this stream 4 to 6 or 7 feet apart. The position of these was very apparent through the breaking of the thin sheet of water over them. Immediately after the formation of these ripples of large amplitude the slackened current produced intermediate ripples at much closer intervals. These quickly resulted in a further slowing down of the current by the damming effect of the ripple-ridges. The reduction of velocity was accompanied by an increase of the volume held on the slope until the current somewhere, usually in upper part of the grade, breached a ripple. This, of course, increased the pressure on the next ripple below which gave way and thus the constantly augmenting volume of water swept away all of the closely placed ripple-marks leaving a smooth slope of sand; then the process was repeated beginning with the formation of the widely spaced ripples. At this peculiarly favourable locality it was thus possible to directly observe under natural conditions the alternate formation and sweeping away of ripple-mark through a slight reduction followed by an increase in current velocity.

Plate III B affords an interesting example of the record, which is sometimes left on the banks of streams, of the work of a current with decreasing velocity. On the left hand side of the picture is seen well-developed ripple-mark which was formed when the stream was at flood stage and the current correspondingly swift. When the water had fallen to the level of the top of the terrace which truncates the ripple-mark pattern, the velocity became too low to form ripple-mark and it began to erode and destroy the pattern previously formed over the whole of the slope shown in the picture. The remaining stages of the retreat were marked by six periods of comparatively rapid withdrawal of the water which are indicated by the small terraces.

As already pointed out the amplitude of dune or wind ripple-mark shows only slight variation. Subaqueous current ripple-mark on the other hand displays an enormous amount of variation in amplitude (Figure 3). This variation of the amplitude appears to depend chiefly on the load of sediment carried and on the velocity of the current. The estuaries of the bay of Fundy afford ample opportunities for studying this variable feature of current ripple-mark. The tidal currents of the bay of Fundy furnish a large variety of the conditions influencing ripple-mark formation. The great range of the tides in the bay, amounting to more than 40 feet at some points (see Plate VI), results in currents of unusual power in the estuaries of the rivers entering this bay. In some of these streams the turn of the tide is accompanied by the phenomenon known as the bore. The advancing tide ascends the river channel in the form of an abrupt steep faced wave 1 to 3 feet high, or as a succession of waves. Both of these phases of the bore are shown on Plate V. Under the influence of the powerful tidal currents heavily loaded with silt, a mammoth type of ripple-mark is developed in many estuaries of the bay of Fundy. The ripple-mark which is most commonly seen along the sea shore and which at most localities is the only kind seen has the ridges spaced at intervals of about 3 inches. This familiar form of ripple-mark is shown on Plate VII. A graded series of these forms can be selected showing ridges varying from a few inches to several feet apart (see Figure 3). The mouth of a stream entering St. Mary bay at the northwest corner just above the bridge affords some striking examples of a large type of ripple-mark produced by the very strong current of the stream at ebb tide. These are remarkable for their large amplitude, the crests being 2 to 4 feet apart and the trough 3 to 6 inches deep (see Plate VIII A). Their large size and nearly flat upstream sides give them a terrace-like appearance. They have less perfect parallelism than ordinary ripples but are, nevertheless, parallel in a general way. In this ripple-mark the lee slopes are inclined at angles of from 25 to 32 degrees and the upstream slopes at $\frac{1}{2}$ to 5 degrees. The profile of an example which was measured is shown in Figure 3 G. The slope of the upstream side is often very irregular and may be trough-like just in front of the steep sloping face.

Sand waves or asymmetrical ripples of mammoth size are developed in the Ottawa river during the flood stage over the broad sand bar at Duck island. In late summer when these are laid bare by low water the crests of the ridges are seen to be 30 to 45 feet apart and 1 to 2 feet above the troughs. These are found on extremely coarse sand.

R. C. Pierce describes sand waves in the San Juan river, California, which are 15 to 20 feet from crest to crest and rise 3 feet above the troughs. "At one moment the stream is running smoothly for a distance of perhaps several hundred yards. Then suddenly a number of waves, usually from 6 to 10, appear. They reach their full size in a few seconds, flow for perhaps two or three minutes, then suddenly disappear. Often for perhaps half a minute before disappearing the crests of the waves go through a combing movement, accompanied by a roaring sound. On first appearance it seems that the waves occupy fixed positions, but by watching them closely it is seen that they move slowly upstream."[1] The upstream movement of the sand-waves doubtless persists only so long as a particular stream velocity is maintained. Similar upstream migration of ordinary ripple-mark has been observed at a stream velocity of 2.2 feet per second.

Examples of large ripple-marks on sand waves were observed at Kingsport, Nova Scotia. Their relations to the other feature of the beach are indicated in the following excerpt from my notes on the Kingsport beach: At low tide the beach exposures at Kingsport may be classed in three groups: (1) the rock ledges and interspersed stretches of sand and gravel beginning 300 yards north of the pier and continuing an undetermined distance in front of sandstone cliffs to the north; (2) the sandy beach extending south from the rock ledges past the pier to the head of the tidal ravine and creek district at south side of town; (3) the mud and clay beach extending southward from (2) and embracing the creek and flats to south.

The beds forming the irregular floor of (1) are nearly all of very coarse Triassic conglomerate including pebbles generally ½ to 4 inches in diameter.

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[1] Water-supply paper 400-C, U.S., Geol. Surv., 1916.

This rock floor is fairly smooth over a portion of its surface and thinly covered with sand in some places; in other places sand and gravel are mixed. In the latter areas the straight parallel lines of ripple-mark formed by the currents of the outgoing tide are beautifully shown. Where sand without gravel is present in the area east of the cliffs the strong outgoing currents develop good examples of large current ripples. These are all of the asymmetrical type, most of them showing an amplitude of 6 inches to 1 foot. But over one stretch of the sand area a mammoth type of ripple-mark similar to that at the head of St. Mary bay is seen: the crests are 5 to 8 feet apart and the troughs 3 to 5 inches deep. A characteristic of all the smaller examples of ripple-mark seen here is the graded character of the materials in them; for the current has left the coarse materials and fine gravel in the troughs, and the sand on the crests and upper slopes (Plate IX B). The mammoth ripples have their crests more scalloped and less nearly parallel than the smaller ones but still show a general parallelism. These large ripple-marks are in many places broken up into an intricate pattern and lose the ordinary ripple-mark characteristics by irregularities in the currents which have breached the crests of the ripple-mark with various irregular slashes not easily referable to any definite type of water sculpture.

In estuaries subject to these unusually strong currents during ebb and flow of the tide, terrace-like waves of sand are often formed, resembling ordinary ripple-mark in all respects except their extraordinary size. This gigantic kind of ripple-mark is developed on the west side of the channel of Avon river near the railway bridge at Windsor, N.S. The abrupt contraction and increased grade of the channel of the Avon river near the Canadian Pacific Railway bridge accelerates the current of the ebb tide as it passes this point. The effect of the swift current heavily loaded with silt in producing "sand-waves"[1] or ripple-marks of enormous amplitude is manifested at low tide when the extensive sandbanks above and below the bridge are laid bare. In the middle of the channel at the bridge the whole of

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[1] Cornish, Vaughn, "Waves of sand and snow," 1914, p. 300.

the sand is removed leaving only rough angular rock boulders on the bottom. Near the west bank, where the current has somewhat less power, the sand remains and ripple-mark forms on sand waves, which have an amplitude of 15 to 20 feet and crests rising 5 to 20 inches above their troughs. The sand flats above these and the monster ripple-mark ridges themselves are covered at low tide with small ripple-mark pattern having an amplitude of 3 inches. A photograph of the large ripple-mark at the Avon River bridge is shown in Plate VIII B. It will be noted that the large ripple-marks are covered with small ripple-marks. The latter were doubtless formed near the end of the ebb tide when the current was comparatively weak and held a smaller volume of sediment than earlier. Both sets trend at right angles to the direction of the current. Plate VII shows the type of ripple-mark formed on the wide sand bars below the bridge by a lighter current. The ripple-mark of both views was formed by the currents of the same tide. Near the east bank above the bridge the swift current, which is strengthened by a wing dam from the west side, keeps the sand swept clean leaving a hard bottom of coarse gravel and small stones. The sand plain which fills most of the river bed elsewhere shows an area of 3 acres or more adjacent to the stony bottom where the currents have been presumably too strong or too irregular to form the sand waves described above. Here the sand is cut into a series of basin-like depressions most irregular in shape and depth (Plate XIII A and B). These range in depth from 3 to 5 feet and in diameter from 3 to 40 feet with outlines of extremely variable shape. This is the type of structure which would result in cross-bedded sandstone. It is in another zone near the west shore where the current must be less powerful that regular "sand waves" are developed.

Vaughn Cornish[1] has found by observation of large sand waves in tidal estuaries in Great Britain that they advance with the tidal current. An average advance of 13 inches, with one ebb tide was found in one case. Cornish also found by a series of observations on large sand waves extending through spring

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[1] Ibid.

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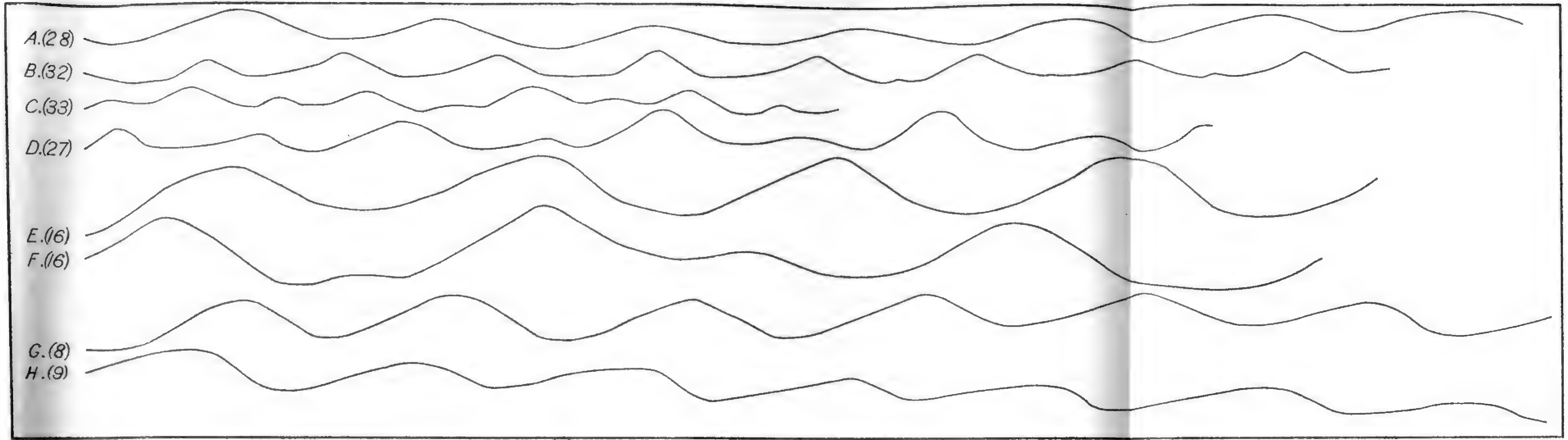

Geological Survey, Canada.

Fig. 4—Symmetrical **wave ripple-mark** profiles (x1.)

A, B, C, D. From lake bottom ripple-mark formed in water 4 inches to 12 inches deep. E and F from water 6 feet deep.

G. From wave formed ripple-mark slightly modified by a weak current in 5 inches of water, S^{t} Lawrence River.

H. From ripple-mark formed under 6 inches of water on S^{t} Lawrence river bottom by wave and current influence combined resulting in asymmetrical crests.

and neap tides that the length or amplitude and the height of the waves were directly related to the stage of the tide. He states that:[1] "As the tides diminished after springs, the length of the waves diminished very slowly, but their height fell off rapidly, and at the time of neap tides they were nearly obliterated, the surface of the sandbank being almost smooth. The average level of the sandbank was, however, unchanged. When the tides increased after neaps, well-defined steep sand-waves were again formed which grew in height and length."

The reason for the formation of the mammoth sized current ripples is not altogether clear at first sight since small ones are developed near them. It has been observed, however, in certain cases that the sand waves lie on a surface sloping with the direction of the main currents where the velocity would probably have its maximum rate. The small ripple pattern associated with the larger forms is in all probability developed in the last stages of the ebb when the velocity of the current is much reduced.

All available observations appear to indicate that current velocity is an important factor in determining the amplitude of current or asymmetric ripple-mark, the amplitude increasing or decreasing with the current velocity. Volume of sediment in suspension is certainly another factor and depth may be a third. With decrease in current a point is reached where ripple-mark is not developed while increase in velocity results, where the bottom is sandy silt, in rapid addition to the load of sediment carried. A strong current carrying a maximum load of sand probably forms ripple-mark of large amplitude where a slightly loaded current having the same velocity would leave no ripple-mark.

SYMMETRICAL RIPPLE-MARK.

A type of ripple-mark which differs distinctly in its perfect symmetry (Figures 3 and 4 and Plate XXI) from the asymmetric current ripple-mark is produced by the oscillation of water resulting from wave action. This is the type of ripple-mark which characterizes the sandy bottoms of lakes and ponds but which is seldom

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[1] "Waves of sand and snow" 1914, p. 316.

seen on the seashore. Since ripple-mark is not uncovered on the lake shore as it is twice daily on the seashore by the ebbing tide, its almost universal occurrence on suitable bottom a few feet or yards from shore in water of moderate depth might never be suspected by the casual observer. Observations made from the lake shore alone, however, would lead to the erroneous conclusion that ripple-mark is not widely or generally present on sandy bottom; for it is developed in water very near the shore-line only where the slope of the bottom is very gentle. Where the shore slopes abruptly under the water ripple-mark is not formed up to the very edge of the beach. A 2-mile walk for example along the sandy beach of lake Ontario near Wellington when the waves are forming ripple-mark would enable one to see ripple-mark along perhaps not more than 100 yards of this distance (Plates XX and XXI). But observations made from a small boat off this shore in water 4 to 10 feet deep would show an uninterrupted stretch of ripple-marked bottom. A water glass or a small wooden box with glass bottom will enable the observer, where the water is clear, to see the wide distribution of wave ripple-mark wherever the bottom is sandy. One of the localities on the Ontario beach, where the slope is sufficiently gentle to permit ripple-mark formation nearly to the edge of the water, is represented in Plate XX A and B, which shows ripple-mark through a very thin cover of water and the advancing waves which have formed it.

Under the conditions generally met with along sandy lake beaches, a broad belt of smooth sand is seen which extends from the upper limit of wave action under the water. The swish of the water from advancing and retreating waves across this zone, varying from a few feet to many yards in width, which is alternately submerged and uncovered does not form ripple-mark. But it leaves a very distinctive and characteristic record of wave action under subaerial conditions in the shape of fine thread-like ridges of sand called wave-marks which mark the maximum reach of the waves at any particular time. The appearance of these is indicated in Plate XIX A. The front of the nearly exhausted wave which makes them is shown in Plate XVIII. The remnant of the breaking wave, which continues up the beach as a thin sheet of water loaded with sand picked up during its advance, drops this load at the instant when it starts back down the beach slope. Wave marks are left only by every third or fourth wave where I have observed their formation. This is due to the fact that they will not form on sand completely saturated with water. A short period, equivalent to that separating the larger waves, suffices to dry the sand to the extent of letting the outer fringe of the larger waves sink instantly into it, thus leaving a little ridge instead of partially carrying back the sand load over a saturated surface. Under a very hot sun the interval between successive waves might suffice for this.

Symmetrical ripple-mark under a few inches of nearly still lake water is shown in Plate XX B. The sharp contrast between the symmetrical or oscillation and the asymmetrical types of ripple-mark can be clearly seen by referring to Figures 3 and 4. The mechanical theory of the formation of oscillation ripple-marks has been developed and the general relation of the essential factors involved has been shown by the work of Hunt, Forel, Darwin, and others. G. K. Gilbert has formulated the essential elements of the theory of their formation in the following passage:

"The ordinary ripple-mark of beaches and rock faces is produced by the to-and-fro motion of the water occasioned by the passage of wind waves. During the passage of a wave each particle of water near the surface rises, moves forward, descends and moves back describing an orbit which is approximately circular. The orbital motion is communicated downward, with gradually diminishing amplitude. Unless the water is deep the orbits below the surface are ellipses, the longer axes being horizontal and close to the bottom the ellipses are nearly flat, so that the water merely swings forward and back. It is in this oscillating current, periodically reversed, that the sand-ripples are formed. A prominence occasions vortices alternately on its two sides, and is thereby developed in a symmetric way with equal slopes and a sharp apex. There is a strong tendency to produce the mole laterally into a ridge, the space between ridges is definitely limited by the interference of vortices and in time there results a regular pattern of parellel ridges, equally spaced. It has been found experimentally that by varying the amplitude of the water oscillation and also by varying its frequency the size of the resulting ripples can be controlled; but the precise laws of control have not been demonstrated. Evidently the frequency of the natural oscillation equals the frequency of the wind waves, and its amplitude is a function of the size of the waves and the depth of the water; so that a relation will ultimately be established between wave-size, wave-period and water-depth as conditions and ripple-size as a result."[1]

The reasons for the initiation of the ripple-mark ridges have been discussed in some detail by Hertha Ayrton.[2]

Although the symmetrical or oscillation ripple-mark is the prevailing type in lake sediments, asymmetric ripples are occasionally developed on lake bottoms by currents set up by storms or other causes. De la Bache[3] as early as 1851 clearly distinguished the wave from the current type of ripple mark, and Prof. F. A. Forrell[4] pointed out many years ago how ripple-marks made by wave action differ in form from those made by river and tidal currents. Prof. Barrell[5] has also noted the marked difference in symmetry between wave and current formed ripple-mark. But geologists appear generally to have failed to appreciate the importance of the distinction, and have made no use of the important clue which the determination of the type of ripple-mark may give concerning the history of a ripple-marked formation.

The symmetrical or oscillation type of ripple-mark is less accessible to study than the current ripple-mark. It is the prevailing type in lake waters where the bottom is sandy and where, owing to the absence of tides, it is seldom uncovered by the water. Examination of symmetrical ripples is, therefore, restricted ordinarily to viewing them through water of varying depths.

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[1] Gilbert, G. K., "Ripple-marks and cross-bedding," Bull. Geol. Soc. Am., vol. X, 1899, pp. 137-138.

[2] "The Origin and growth of ripple-mark," Proc. Roy. Soc., London, vol. 84, 1911, pp. 285-310.

[3] The Geological observer, 1851, pp. 607-610.

[4] Bull. de la Société Vandoise des Sciences Naturelles, Feb. 1878.

[5] Bull. Geol. Soc. Am., vol. XXIII, 1912, p. 432.

On the seashore, where the current of the ebbing tide nearly always develops the asymmetric or current ripple-mark type, the retreat of the tide removes every obstacle to close examination. The numerous photographs of ripple-mark uncovered by the tide, which have been published, consequently show current ripple-mark but not oscillation ripple-mark. The photographs and profiles of wave ripple-mark, which are here shown, have been obtained by making, under water, plaster moulds of these ripple-marks. The method used in taking these preserves perfectly the finest details, notwithstanding the fact that they are composed of material so unstable as sand.

Symmetrical ripples do not travel like the asymmetrical or current ripple-mark. They maintain a permanent position so long as the conditions which produced them remain unchanged. In specimens of fossil ripple-marks in the Joggins, N.S., section, I have observed symmetrical ripple-marks directly superimposed throughout a bed of sandstone 6 inches thick. Gilbert records an observation in which the lamination of the strata showed that a set of ripple-marks had held the same position while 2 feet of sediment were accumulated.[1]

All waves have a tendency, whatever their direction may be at a distance from the shore, to change gradually the direction in which they are trending as they approach land and enter shoal water, so that they reach the beach with troughs and crests approximately parallel to it. "The action of the bottom on a wave may be compared to that of a friction brake on a machine." The end of a wave which first "feels the bottom" in shallow water will slacken its speed while the opposite end in deeper water travels faster, thus causing the entire wave in approaching shore to swing round and face the beach. As a result of this tendency of waves to face the beach in approaching land, the ripple-marks made by them always trend with the direction of the strand line near the shore. On the shores of lakes where ripple-mark is due entirely to wave action it always runs parallel with the coast-line. Ripple-mark along the sea coast is generally the work of tidal currents which follow the shore-line. These

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[1] Bull. Phil. Soc., Washington, vol. 2, 1874-78, pp. 61-62.

current made ripple-marks consequently trend at right angles to the coast-line. Lake shore and sea shore ripple-mark are thus differently oriented with respect to their adjacent shore-lines, the former trending with the shore-line, the latter at right angles to it.

The relationship which the amplitude of wave-made ripple-mark bears to depth is a subject which needs further investigation before any final conclusion can be formulated. Mrs. Hertha Ayrton[1] concludes as a result of experimental work on ripple-mark in small tanks: "But as the heights and ripple-distances of all vary with the amplitude of the wave, they are greater after a storm than during calm weather." My own observations on ripple-mark in water from 1 to 25 feet deep do not appear to sustain this opinion. Little if any change in the amplitude of ripple-mark was observed after periods of stormy weather. Mrs. Ayrton also states that the side of a ripple facing the shore is steeper[2] than the opposite side. None of the numerous wave ripple-mark moulds which I have taken under water, however, show any modification of symmetry with reference to the shore-line. The precise relative influence which depth and wave amplitude have on the height and spacing of ripple-mark has not yet been ascertained, although the observations made indicate that depth is one of the factors controlling amplitude of ripple-mark. Observations in shallow water clearly show an increase in the size of the ripple-mark ridges and troughs with increasing depth; to what depth and at what rate this increase will extend remains to be determined. A large number of observations on ripple-mark in water less than 6 inches deep indicate that the crests of the ripples at this depth are never more than 1 or 2 inches apart. In water 3 to 10 feet deep the crests are from 2½ to 5 inches apart. The following series of observations taken near Wellington in water ranging in depth from 15 inches to 20 feet will suffice to show one example of the evidence secured on this problem.

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[1] Proc. Roy. Soc. Lond, ser. A, vol. 84, 1911, p. 307.

[2] Ibid, p. 305.

Depth of water.	Amplitude of ripple-mark.
15 in.	2 to 4 in.
2½ ft.	3½ to 4 in.
10 ft.	4 to 6 in.
11 ft.	4½ in.
20 ft.	4 to 5 ft.

The large number of observations which have been made on ripple-mark in depths between 6 inches and 10 feet may be summarized in the statement that the amplitude at the former depth varies between 1 and 2 inches and at the latter between 3½ and 6 inches. Ripple-mark with an amplitude of less than 2 inches is, so far as my observation goes, formed only in water having a depth of less than one foot.

It is probable that the factors controlling amplitude and height of crest in symmetrical ripple-mark include coarseness of sand, depth of water, and wave amplitude. Much additional work is needed to determine the relative importance of these factors.

RIPPLE-MARK OF IMBRICATED OR COMPLEX PATTERN.

The more simple and common forms of ripple-mark are included in the two types which have already been described. The more complex forms resulting from various combinations of these fundamental types will now be considered. Ripple-mark of simple type is often modified by the superposition upon it of another type thus producing a complex or complicated pattern. The relationship of the different features of these complex forms of ripple-mark to the factors producing them has been ascertained in many cases by observation of them as they emerge from the ebbing tide.

Ripple-mark developed by current action is frequently modified by wave action. If the wind should blow at right angles to the course of a stream in which current mark is forming, or transverse to the direction of a tidal current, the ripple-mark resulting from these currents will be crossed transversely by ripple-mark which trends at right angles to the course of the wind. If the waves are the product of a moderate breeze and are of small size the current ripple-mark will be marked on its gentle slopes only by a miniature ripple-mark pattern which will be broken or interrupted by the troughs of the current ripples. This type of ripple-mark is shown in Plates IX A, XV B, XXVII, XXVIII B, and XXIX. The size or prominence of these superimposed ripples will depend on the strength of the waves producing them. Under the influence of a strong wind they will develop to the extent of breaking across the current ripple pattern and produce a knobby surface like that shown in Plate XV C. The ripple-mark superimposed on the current mark by wave action is always of the asymmetrical type owing to the influence of the current upon it, as will be seen by an examination of Plate IX A. The current ripples and superposed wave ripples shown in the photograph on Plate XV were formed under water and air conditions which were closely observed. These conditions are indicated in the following excerpt from my notes: The mud bank of the east shore of the Avon river, 1½ miles below Windsor, slopes gently toward a broad sand plain 100 to 250 yards wide which is nearly flat and uncovered at low tide. This sand flat is beautifully ripple-marked throughout at low tide, when there has been little or no wind, by regular ripples with an amplitude of 3 to 3½ inches. These are to-day rippled at right angles by very small ripples caused by the waves set up by the strong westerly breeze which has been blowing during ebb tide. These small ripples of wave origin over considerable areas are of one inch amplitude. At lower levels where the ripple-mark formed after the breeze dropped somewhat, these superposed ripple-marks are much smaller, making only small ridges one-fourth to one-third inch apart on the steep and gentle slopes of the current-ripples.

Wave ripple-mark is subject to modification by current action, the resulting form depending on the strength of the current. The symmetrical crests of wave-ripples are extremely sensitive even to very gentle current action. A current which is barely perceptible is sufficient to modify wave-made ripple-mark and give it a slightly asymmetrical form. These slight modifications of the symmetry of wave ripple-marks can seldom be clearly recognized in observations made through the water but are easily seen in the plaster moulds. Many observations on the influence of current on wave-made ripple-mark were made along the St. Lawrence river. The breadth of the river, and the generally sandy shores along parts of its course above lake St. Peter afford favourable conditions for the formation of ripple-mark by wave action, in the very shallow water along shore where the current alone is not strong enough to produce ripple-mark. Where the current is strong in the deeper water of the river, true current ripples unaffected by wave action are doubtless formed where the bottom is suitable but these were not observed.

We are at present concerned only with ripple-mark developed along the shore by waves produced by the wind. These are generally parallel with the shore. In one case symmetrical wave ripple-marks were observed within 4 feet of ripple-marks which though due primarily to wave action had been given an asymmetric form by the very gentle current which reached them. Examples of the two types within a few feet of each other were marked and the symmetrical ripple-mark was found to be stationary while the asymmetrical forms a few feet away moved 1¼ inches in 25 minutes. At a point above Lanoraie, Que., on the west bank of the St. Lawrence, the following notes were made on the wave-made ripple-marks observed: A strong upstream breeze makes waves out in deep water transverse to the channel; but along the beach waves come in parallel to the beach with crests 6 to 10 inches high and 4 to 8 feet apart. These have kept the bottom rippled in the shallowest water (1 to 5 inches) with asymmetrical ripples with crests about 1½ to 1¼ inches apart. Three of these were marked and observed. Their crests moved shorewards a distance equal to their amplitude (crest to crest 1½ inches) in 20 minutes. Water was 3 inches deep. Above observations were repeated in 6 inches of water where crests are 2 inches apart; ripples moved shorewards at the same rate, viz., distance of amplitude, 2 inches, in 20 minutes.

Comparison of the profile (Figure 4 G) of the moulds of modified wave ripple-mark taken at Lanoraie with typical current ripple-mark profiles from Windsor (Figure 3 C and D) shows a marked difference in the degree of asymmetry, the latter showing a very much steeper lee slope than the former. There is considerable difference in this respect also among the current modified ripples, some specimens like Figure 4 G showing a barely perceptible amount of asymmetry.

Observations and photographs of ripple-mark phenomena at Annisquam, Mass., accompanied by a sketch map and cross section which were kindly placed at my disposal by Mr. G. K. Gilbert[1] illustrate some of the ripple-mark patterns which result from the joint work of wave and current action when opposed to each other. Mr. Gilbert writes regarding the Annisquam ripple-mark: "When the currents are strong the ripples assume the character of subaqueous dunes with rounded crests and foreset beds at the angle of instability; and when the currents move in a different direction from the wind waves the ridge crests break up in a rhythmic way, giving a sort of imbricated pattern. I had an opportunity to study this phenomena at Annisquam, Mass., where I spent the summers of 1911 and 1912.

"Figure 5 shows the relations of a sand spit to a broad shoal on one side and a tidal channel on the other. There is a large estuary to furnish strong tidal currents, and these currents not only follow the channel but cross the bar obliquely —an arrow shows the direction of the outgoing tide, and another arrow the general direction of approaching waves and ground swells. On the shoal are ripple-marks of ordinary type. On the spit, each storm from the north, and each period of heavy ground swell, develops large ripples and these nearly always assume the imbricated pattern. When exposed at low tide they are asymmetric, with the lee side toward the ocean, and thus facing obliquely against the formative water waves. They are formed under 5 feet or more of water, and their size varies with the depth. That is they are smallest at C and grow larger toward D (see cross section, Figure 5). I was able to trace them to about 10 feet below low tide level. Often they are covered by ripple-marks of smaller size which I assume to have been formed after the water had become shallow on the spit; and in the hollows of the pattern are still smaller ripple-marks. I enclose photographs. The oar is 7 feet long. The photograph (Plate XIV A) looks along the spit toward rocks at E, while Plate XIV B looks in the opposite direction. The largest examples of ripple-mark seen measured about 15 feet from crest to crest and about 15 inches in height."

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[1] Letter to the author, Jan. 16, 1914.

Other observations of Mr. Gilbert[1] on ripple-mark of complex pattern are as follows: "While at the seashore in the summers of 1911 and 1912 I visited almost daily a sand spit bare at low tide and saw each day a new pattern of ripple-mark. Cross patterns were common—or rather not rare—but only a few of them indicated equal action in two directions. Usually a system of parallel ridges was given an appearance of reticulation by systematic offsets the lines of offsets making 60 degrees with the trend of ridges. As the lines of offsets were not equally spaced I did not refer them to a crossing system of water waves. Occasionally there were two systems of offsets producing a pattern with three directions. Not rarely the crests of the ridges were

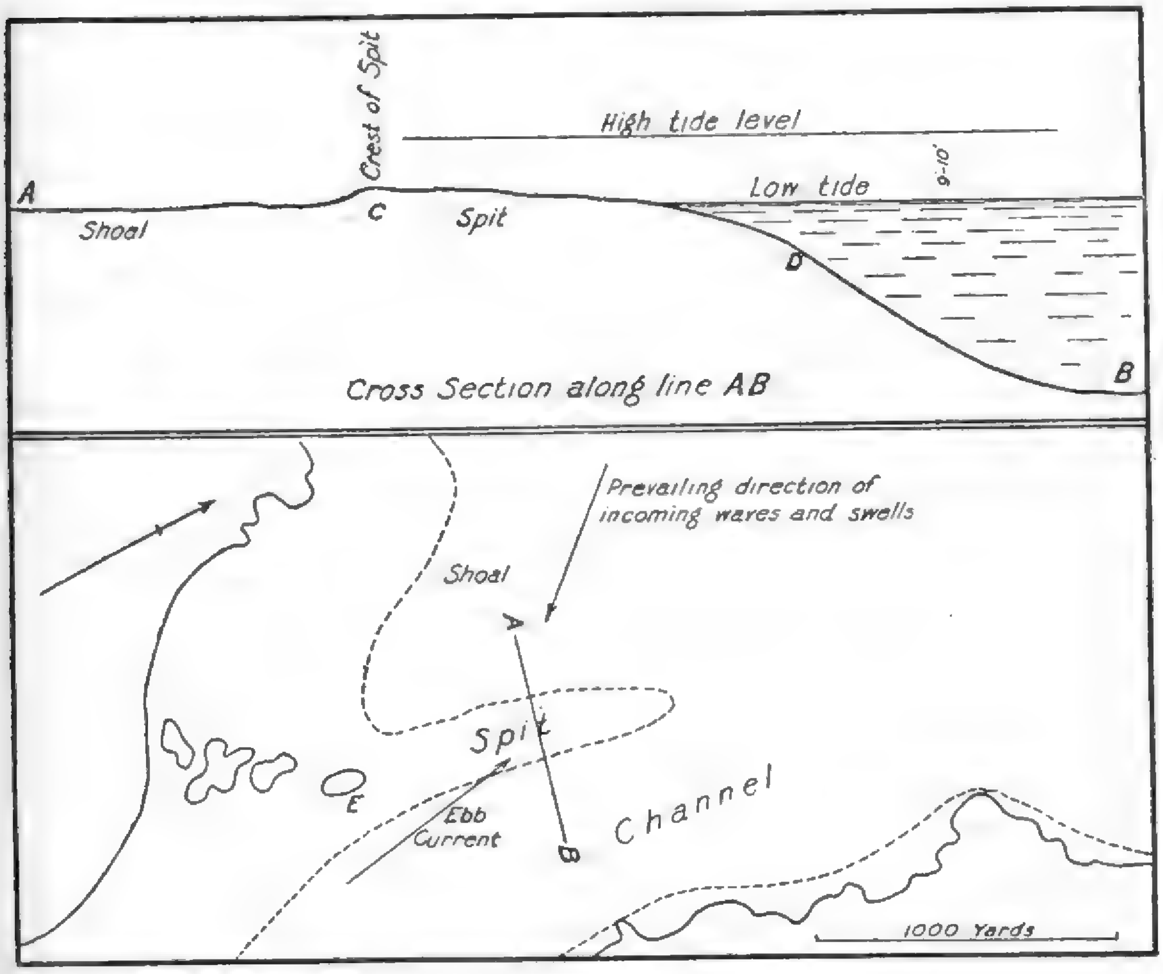

Figure 5. Entrance to Squam estuary, Mass., with section along A B. Heavy lines, high water; dotted lines, low water. The figure illustrates conditions under which ripple-mark shown in Plate XIV was developed.

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[1] Letter of Dec. 12, 1913.

double, a character I have noted also in fossil examples. Sometimes the whole system of ripples would take the character of dunes and in that case the pattern was usually imbricated. One might say that the dunes fell into two sets of rows of which the directions made an angle less than 90 degrees or that the surface was occupied by two systems of ridges, at the intersections of which were special developments.

I also saw something of the process of ripple making, observing the eddies in the intervening hollows and the cloud of sand projected from each crest as a water wave passed over.

By the way this reticulated pattern of subaqueous dunes is the feature in the Portage formation which Hall called mud flow. The material is sand rather than mud and the form is developed (at Annisquam) by the joint action of waves and current."

One of the unusual varieties of ripple-mark pattern is shown in Plate XIX B, which was photographed from a mould taken at the edge of the beach near Port Colborne on lake Erie. This example is the result of the action of very small waves lapping and crossing each other from opposite sides of a miniature spit. The position of a small partially submerged outward projecting point of sand bar supplied the conditions for complex wave action in the lee of the bar.

INTERFERENCE RIPPLE-MARK.

A form of ripple-mark which has little resemblance to the ordinary forms is generally designated as interference ripple-mark. It has been called "dimpled current mark" by Jukes. It has sometimes been described under the name of "tadpole nests"[1] with reference to its supposed origin. In place of the parallel trough and ridge structure of the common forms of ripple-mark a deeply pitted or cell-like structure is characteristic of interference ripple-marks (Plates XXII and XXIII). I have found that different examples of interference ripples show a rather wide range of characteristics with respect to the appearance of the pits or cells comprising them. Just as ordinary ripple-

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[1] E. M. Kindle, "An inquiry into the origin of 'Batrachoides the Antiquor' of the Lockport dolomite of New York," Geol. Mag., dec. VI, vol. 1, 1914, pp. 158-161.

marks show crests, which, in examples produced under different conditions, range from sharply angular to nearly flat or rounded, so interference ripples exhibit corresponding variations of type. Successive observations of one set of interference ripples, continued for three days, have also shown that aging of the impressions, under the influence of a shifting direction of the wind, tends to alter angular partitions to rounded ones, thus producing patterns resembling the "tadpole nests" of Hitchcock. The comparative rarity of the so-called "tadpole nests" affords strong evidence that they are the product of the wind rather than of tadpoles. I have observed many scores of ponds with tadpoles, but have only once seen the dimpled surface called "tadpole nests" by Hitchcock associated with tadpoles. Interference ripples are much less common than the wave-like type of ripple-mark so frequently seen in shallow water. They are developed under shallow water in which the ordinary wave generated by the action of the wind on the surface is split up into two or more sets of oscillations moving in different directions. The gradual movement of fine sediments by such conflicting oscillations results in the coarse cell-like structure shown in Plate XXII. The interruption or breaking up of regular wave oscillation, which occurs about the ends of bars, piers, or stranded logs, affords favourable conditions for the development of interference ripples. When the bottom is favourable interference ripples are generally found in the shallow water of such localities. The cast of the interference ripples shown in Plate XXIII C was made in water about 6 inches deep and protected on all sides by stranded logs from any but the lightest wave action. The photograph shown in Plate XXII was taken from a plaster mould of interference ripples made under a few inches of water at Britannia bay, Ontario, where the regular wave oscillations are interrupted by the pier and stranded logs. This picture indicates the close relationship of the interference ripple-mark to ordinary wave ripple-mark. The lower half of the picture shows a type belonging more to the ordinary oscillation ripple than to the interference form. The upper half shows the troughs of the oscillation ripples broken up by a series of more or less discontinuous partitions giving the effect of a series of foursided cells. In the waters of small shallow ponds development of interference ripples frequently occurs in which the cells have rounded instead of quadrangular sides. A photograph of this kind of interference ripple-mark is shown in Plate XXIII A which shows the bottom of a small pond from which most of the water has evaporated leaving the interference ripple-mark structure exposed on the surface. Interference ripple-mark is frequently seen in miniature coves or identations of the shore-line but never along a straight uninterrupted shore-line. The Triassic sandstone of the Connecticut valley has furnished some striking fossil examples of this type of ripple-mark. It was originally described by Hitchcock from these beds as "tadpole nests."[1] It also occurs, though rarely, in the Berea sandstone, as shown by Plate XXX B.

CURRENT-MARK.

In preceding pages it has been shown that water currents passing over sand at certain velocities develop ripple-mark over the whole surface; at other velocities the surface film of sand is moved along in a uniform sheet without the formation of ripple-mark and the surface is left smooth. If the sand transporting current joins a slower current or enters quiet water its load is thrown down in a fan-shaped mass called a delta (see Plate XVI A). When converging currents meet or, where owing to irregular contour of the bottom or sides of the channel, variable or irregular currents are developed, there results an intricate interplay of the forces tending to produce ripple-mark and those tending toward delta formation. Instead of the regular rhythmic succession of ridges and furrows of ordinary ripple-mark variable currents often produce a great variety of irregularly mammillated and lip-shaped surfaces on sandy bottom which may be called current mark (Plate XVII and Figure 6). Jukes has described this type of current sculpture and its cause as follows:

"In places where the current was troubled a modification of these rippled surfaces is sometimes produced, the bed being

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[1] "Ichnology of Mass.", pl. I, fig. 1, 1858.

irregularly mammillated on its surface, which is pretty equally, although irregularly divided into small hollows and protuberances of a few inches in diameter."........"It might be called dimpled current-mark."[1] Strong currents which impinge upon each other over a sand bar which lies between two channels are apt to produce this phase of water sculpture showing a peculiar pendant and elongated lip-like effect. Examples of this phase of current mark are shown in Plates XVI B and XVII A and B. Plate XVII B and C represents current-mark which was made by a small brook near its junction with the St. Lawrence river. Plate XVII A is from the mould of a cast taken on the sand bar at the mouth of the Avon river. Plate IV A shows the appearance of the surface of a small brook near Ottawa which is flowing over a sandy bottom and producing in parts of its channel a variety of current-mark. Two lines of tongue-like ripples on the surface of the brook indicate the zones of maximum bottom ridging. Where these two lines of ripple unite below the small bar current-mark is formed. This photograph clearly shows the varying intensity of the action of the current in different parts of the bottom of the narrow channel shown. The different types of current mark are all apparently the result of irregular or "troubled" currents. Some of these, like the structure shown in Plate XVI B, have the appearance of mud flows.

Many geologists have been puzzled by these curious features on the surface of stratified rocks and they are frequently erroneously called "mud flows" in geological reports. Jas. Hall[2] figured examples of this structure as "casts of flowing mud." David Dale Owen[3] figured a fine example of current mark but wrote "I am rather disposed to the belief that the material of which the rock is composed was once volcanic mud and that while in a viscid state, it congealed suddenly, or became fixed in the very act of flowing down the hillside; transmitting to us a lapidified memento of the action of some mud volcano in the vicinity." The peculiar impressions left by the swirl of waters on sand in eddying currents resembles often the sweeping

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[1] J. B. Jukes, Manual of geology, 1872, pp. 163-164.

[2] Geology of New York, pt. 4, fig. 10, 1843, p. 233.

[3] Illustrations to the Geol. Rept. of Wis., Iowa, and Minn., table I, fig, 1, 1852.

curves of a rooster's tail feathers. Some of the described species of *Taonurus* are probably of current rather than plant origin. Typical examples of fossil current mark are common in the lower part of the Joggins section, N.S., at the old grindstone quarry. The Aylmer sandstone at Ottawa is nearly always characterized by these impressions. Plates XXXI and XXXIII show examples of current mark from the lower part of the Joggins section.

DEPTH TO WHICH RIPPLE-MARK EXTENDS.

The discussions of ripple-mark found in many texts and treatises on general geology treat them as shallow water features. LeConte[1] states that "By means of these characteristics of shore deposit (ripple-marks) many coast lines of previous geological epochs have been determined." A bulletin of the United States Geological Survey, intended primarily for use in schools and colleges, informs the student that: "In the water they (ripple-marks) are formed only where it is shallow and they do not extend beyond the depths to which the water is agitated by the wind."[2] Fossil ripple-mark has thus come to be regarded by many geologists as a criterion of very shallow water conditions. This conception of ripple-mark has no doubt arisen chiefly through the fact that direct observation of it has been limited to shallow water. But we have little better reason for assuming that ripple-mark extends no deeper than it has been actually seen, than we have for inferring that the natural habitat of fishes extends no deeper than we have actually observed them.

Curiously enough the statements regarding ripple-mark contained in some of the older text books are much more accurate than are discussions of the same subject in many of the more recent manuals. Thus the statement of Jukes regarding ripple-mark produced by current action requires no revision at present. He writes: "A rippled surface, therefore, to a rock, is no proof of its having been necessarily formed in shallow water, though rippled surfaces are perhaps more frequently formed there, but simply a proof of a current in the water sufficient to move

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[1] Elements of geology, 1888, p. 3a.

[2] J. S. Diller, "The educational series of rock specimens collected and distributed by the U. S. Geol. Survey," Bull. U.S.G.S., No. 150, 1898, p. 82.

the sand at its bottom gently along at whatever depth that bottom may be from the surface of the water."[1] This entirely correct statement removes ripple-mark from the list of features which can be regarded as evidence of shallow water conditions.

Among the earliest observations on the depth to which wave action extends are those of Siau.[2] A translation of his description of the ingenious methods of observation used and his conclusions follow:

"The observations which we record were made on white madreporic and black basaltic sand bottoms. They were made during the course of examinations in connection with the establishment of a harbour at Sant Gilles where there is a natural channel current through the coral reef that lies along the coast.

"When the sea is calm enough to allow the gravelly sand of the channel bed to be seen, parallel ripple-marks may be discerned, the transverse section of which changes with the state of the sea which causes their formation. On the occasions when observation was possible the distance between two consecutive troughs or two crests was estimated to be 30 to 50 centimetres, the depth of the trough below the crest being about 10 to 15 centimetres.

"The heavier materials such as coarse sand, gravel and small stones are found in the hollows of the undulations and the finer sand at the summits.

"When the ripples are made up of materials of the same size but of differing specific gravities, like basaltic and calcareous sand, the heavier materials are found in the hollows and the lighter at the summits.

"It may be readily seen that the undulations are due to the actions of the waves. When the water is undisturbed and the bottom is visible, the waves have very slight effect on it; but when the water is agitated, the materials are set in motion. Little by little as the waves decrease, their effective action diminishes, until they are no longer able to move the heavier

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[1] Manual of geology, 1857, p. 172.

[2] Siau, "De l'action des vagnes à de grandes profondeurs," Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences. Tome XII, 1841, pp. 770-776.

particles. Sifting or sorting then takes place; the lighter particles are separated and continue to move forward as before, still in the undulatory course which the movement always follows; the wave action stirring up the bottom of the troughs, carries the fine particles to the crests, leaving the heavier material uncovered in the hollows.

"Advancing along the channel toward the entrance, it was seen that the ripple-marks maintained their parallelism and that their section gradually diminished. The same is true in the open sea, the undulations there are parallel to those in the channel. Alternating zones of heavier and lighter material can always be distinguished and they may be easily seen, when the sea is calm, at depths of at least 20 metres.

"Proceeding farther out to sea and making soundings with a lead charged with tallow, it was found on raising the lead that the zones above referred to were stamped on the tallow. Sometimes a uniform zone of heavy material was brought up and the tallow had a convex surface or, again, a zone of light particles was brought up when the tallow had a concave form. Finally, at great depths, two narrow zones of fine particles of different specific gravities were brought up together and it was noted that the heavier particles covered a protuberance in the tallow and the lighter, a depression.

"These considerations have led us to recognize that, where our observations were made, the motion of the sea makes itself felt at greater depths than have been recorded by previous observers, who have worked in a less precise way.

"We regret that time and circumstances prevented us from making further research, for the nature of the bottom in which we were working was favourable for such observations because of its being made up of materials of different specific gravities and of different colours.

"The deepest sounding which has been definitely recorded was one of 188 metres (578 feet) made in St. Paul channel on a basaltic sand and gravel bottom. In this case the occurrence of zones was recognized by the clearest evidence.

"Soundings were made also at much greater depths, but while the results seemed to us to be in all probability analogous to those quoted we have not cited them in the absence of their confirmation by further observations."

In recognizing the importance of these observations it is necessary to point out that Siau fails to consider the possibility that the ripple-marks which he found at such great depths may have been caused by tidal currents. While this possibility does not seem very probable to the writer it must nevertheless be taken into account and until eliminated the parallel zones or ridges found by Siau at 578 feet cannot be considered conclusive evidence of wave action at that depth.

Rather sharply contrasted with Siau's statement that he observed ripple-mark with crests 11 to 20 inches apart is Pirsson and Schuchert's[1] report of Prof. Verrill's observation near the island of Anticosti. "Ripple-marks have been seen and measured in depths of 75 feet with the ridges still 3 inches apart." It is possible that the discrepancy between the two statements with reference to amplitude at a considerable depth may be due to the greater amplitude being the product of wave action and the lesser the result of tidal current action. It is not stated how the ripple-mark was "seen and measured" at the considerable depth of 75 feet.

The statements of some geologists who have had opportunities for examining the sea bottom through the clear sea water and brilliant light which prevails on sub-tropical coasts indicate that under these favourable conditions ripple-marks may be seen from the surface at considerable depths. Prof. John L. Rich[2] states that, "I have seen from a glass-bottomed boat ripple-marks developing in water estimated to be 70 or 80 feet deep, at Avalon, California, under the influence of the ocean swell. At Avalon in the deeper water the ripple-marks might be likened more nearly to windrows than to anything we are likely to think of as ripple-marks. They must have been 5 or 6 feet apart and 1 or 2 feet in height."

The only observations of my own bearing on this question were made in lake Ontario. In the bay at Wellington on lake Ontario, I was able one still, bright day to observe ripple-marks

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[1] Pirsson and Schuchert, "A text book of geology," 1915, p. 491.

[2] Letter to the author, Feb. 15, 1915.

which extended continuously over the bottom from a depth of 1 foot near shore to 19 feet about one-third of a mile from shore. They were seen very clearly to a depth of 15 feet, and less distinctly to 19 feet and beyond that depth vision failed. A sounding lead drawn over the bottom showed clearly by the jerking pull on the line that the ripple-marks continued out into water about 24 feet deep. Beyond this depth the increased depth of water takes up or modifies the vibration on the line to such an extent as to cause this method to give no precise information regarding ripple-mark. Attempts to secure plaster moulds of ripple-mark in 30 feet of water failed, apparently because of the strong bottom current which undercut the edges of the apparatus before the plaster had hardened. The greatest depth at which I have taken moulds of ripple-mark is 27 feet.

In considering the maximum depth at which ripple-mark may occur it is important to discuss separately the two kinds of subaqueous ripple-marks which have been described. The symmetrical type of ripple-mark produced by wave action will certainly be developed on sandy beds at any depth to which the effective oscillatory movement of waves extends. I have shown elsewhere[1] that wave action of an extremely vigorous type extends to depths of 10 fathoms in lake Ontario. Wave action which is violent enough to break up a lake tug at a depth of 10 fathoms could hardly fail to make itself felt on the bottom at several times that depth. Fifty fathoms would seem to be a conservative estimate of the depth at which ordinary storm waves would develop ripple-marks on the bottom. With reference to this question Dana stated that:[2] "Ripple may form over the bottom as far down as the oscillation in the water extends, which may be a hundred yards or more."

In the case of asymmetrical ripple-mark the only factors essential to their formation are current action and suitable bottom material. There is no reason why both of these may not be found at any depth known in epicontinental waters. Unlike wave action current action may extend to any depth. Current ripple-marks may, therefore, be formed at great depths.

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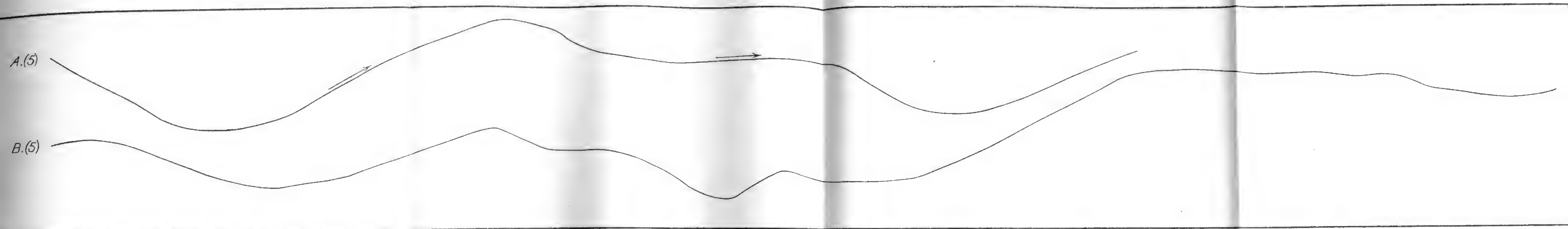
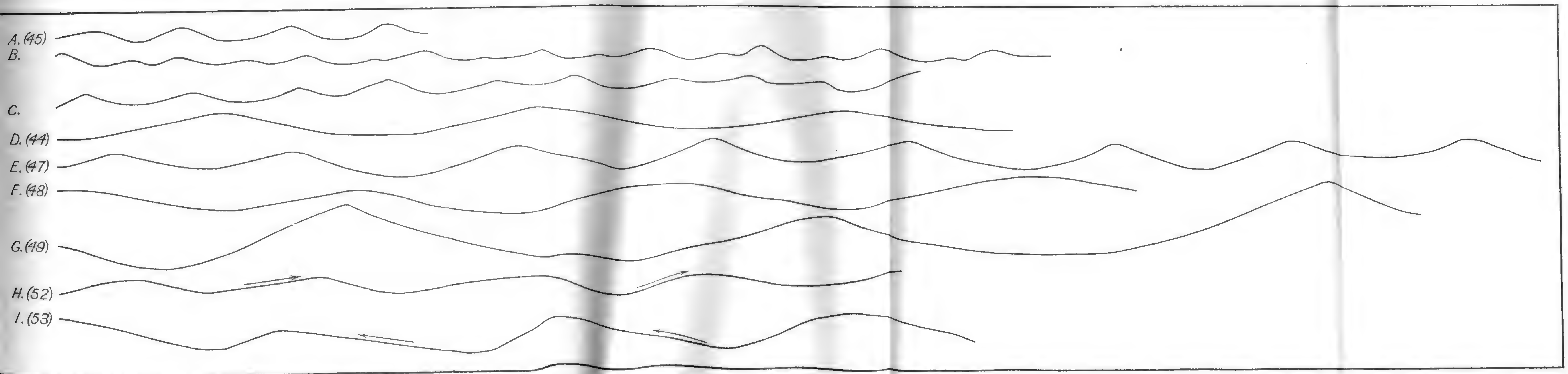
[1] Sedimentation in lake Ontario, MS.

[2] J. D. Dana, Manual of geology, 4th. ed., 1895, p. 94.



eological Survey, Canada.

*Fig. 6 – **Current**–mark profiles (x1.)*
A. Taken from cast shown in pl. 17, A. parallel to direction of current.
B. Taken at right angles to profiles A.



eological Survey, Canada.

*Fig. 7– **Ripple-mark** profiles on sandstone (x1.)*
A–C From wave formed ripple-mark on Cretaceous sandstone (B and C are from ripple-mark shown on plate 24) D to G. represent wave developed ripple-mark on Carboniferous sandstone formed in deeper water than B and C. (Pl. 25, B. shows photograph of slab which furnished E. H and I are from Carboniferous and Cambrian ripple mark developed by currents) (See pl. 27, A. , for original of I.)

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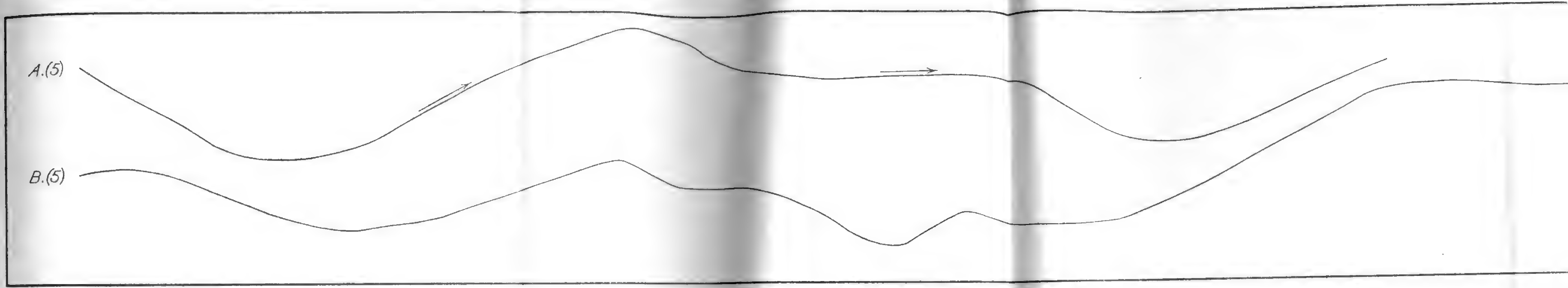
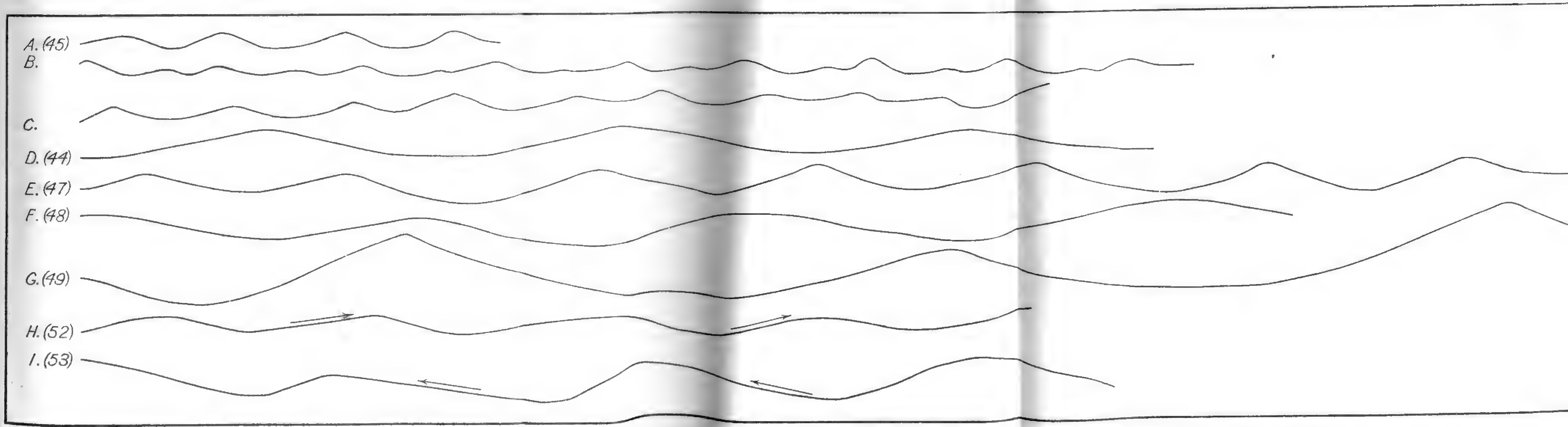
ed., 1895, p. 94.



Geological Survey, Canada.

*Fig. 6 – **Current – mark** profiles (x1)*
A. Taken from cast shown in pl. 17, A. parallel to direction of current.
B. Taken at right angles to profiles A.



Geological Survey, Canada.

*Fig. 7 – **Ripple-mark** profiles on sandstone (x1)*
A–C. From wave formed ripple-mark on Cretaceous sandstone (B and C are from ripple-mark shown on plate 24) D to G. represent wave developed ripple-mark on Carboniferous sandstone formed in deeper water than B and C. (Pl. 25, B. shows photograph of slab which furnished E. H and I are from Carboniferous and Cambrian ripple mark developed by currents) (See pl. 27, A. , for original of I.)

FOSSIL RIPPLE-MARK AND ITS INTERPRETATION.

FOSSIL RIPPLE-MARK CHARACTERISTICS AND HORIZONS.

Sandstone formations which are conspicuously ripple-marked occur at horizons ranging in age from the Pre-Cambrian to the present. These fossil ripple-mark impressions include all of the types which have been described in preceding pages. Examples of wave formed ripple-mark as it appears in sandstone are illustrated both by profiles and photographs in Figure 7 A to G and in Plates XXIV, XXV, and XXVI. The appearance of Palæozoic fossil current ripple-mark is shown in Plates XXVII and XXVIII and Figure 7 H and I. Besides the two simple fundamental types of symmetrical and asymmetrical ripples which record precise evidence of the movement of the ancient waves and the direction of currents which produced them, the sandstones afford good examples of current marks (Plates XXXI and XXXIII) and of interference ripple-mark (Plate XXX). Even the transverse, secondary, ripple ridges impressed on an ancient sand by a shifting wind are found on ripple-marked sandstone (Plate XXXII A).

Geological reports dealing with sandstone formations seldom fail to mention ripple-mark as a characteristic of certain beds. They generally neglect to state, however, the type of ripple-mark represented. Beautifully preserved ripple-mark of both symmetrical and asymmetrical type occur in the Huronian. A good example of asymmetrical or current ripple-mark from the lower Huronian found at lake Chibougamau, Quebec, has been figured in a report by Faribault, Gwillim, and Barlow.[1]

Photographs published by Hore[2] show ripple-mark of symmetrical type in the Huronian of Ontario.

In southeastern British Columbia, Daly[3] has described a quartzite formation 1,650 feet thick called the Ripple formation, which he referred to the Lower Cambrian, but which has since been placed in the Pre-Cambrian by Schofield.[4] These quartz-

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[1] "Report on geology and mineral resources, Chibougamau region, Quebec", Mines Branch, Quebec, 1911, p. 136.

[2] Mich. Acad. Sc. Rept., vol. 15, 1913, p. 59.

[3] Geol. Surv., Can., Mem. 38, pt. I, 1912, pp. 155-156, plates XVII and XVIII.

[4] Geol. Surv., Can., Mus. Bull. 2, 1914, pp. 79-91.

ites are characterized by ripple-mark in a very perfect state of preservation according to Daly who states that: "A principal feature of the quartzite is the occurrence of extremely well-preserved ripple-marks at various horizons. On Mt. Ripple itself these markings are exposed in a truly spectacular fashion. In bed after bed for a thickness of several hundred feet together the surfaces of the old sand were moulded into typical ripples of highly varied orientation. As exposed on bedding-planes these marks are to-day apparently as sharply marked as they were when each bed was just covered by the next wash of sand. Whole cliffs are ornamented with the strong ridges and troughs of the ripples themselves or with their negative impressions."

The Potsdam sandstone of the Cambrian is beautifully ripple-marked at many localities. Good examples of ripple-mark at this horizon may be seen at South March quarry near Ottawa, Ontario, in the quarries near Montebello, Quebec, and at Hammond, New York. Photographs of both current and wave ripple-marks from the first locality have been published elsewhere.[1]

At South March quarry the rock is a hard, white to buffish-grey, moderately coarse sandstone. It is thin-bedded, lying in strata 2 to 10 inches thick. Some of the strata are beautifully ripple-marked. All of the ripple-marked beds and those associated with them appear to be quite barren of fossils, although a *Lingulepis acuminata* Con. occurs abundantly a little lower in the section along the railway. Two distinct types of ripple-mark, symmetrical and asymmetrical, occur in the highest beds exposed on the hilltop.

Perhaps no formation is more uniformly and generally ripple-marked than the Berea sandstone at the base of the Carboniferous section of Ohio and northern Kentucky. The sandstone has been described by E. B. Andrews[2] and Orton and later by Hyde[3] who studied it with reference to the evidence it afforded on the palæogeography of its epoch.

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[1] Kindle, E. M., Jour. Geol., vol. XXII, pp. 704-705, figure 2.

[2] Geol. Surv., Ohio, Rept. Prog. (1869) in 2d. dist., ed. 1870, p. 68; ed. 1871, p. 72.

[3] Jour. Geol., vol. 19, 1911, pp. 257-269.

In the Coal Measures, sections at Joggins and at Sidney, Nova Scotia, afford notable examples of ripple-mark horizons.

While ripple-mark is a very common characteristic of the sandstone horizons mentioned as well as of many others, it is worthy of note that it is absent or extremely rare in various other sandstone horizons.

Although familiar with numerous sections of the Oriskany sandstone along its entire line of outcrop from Ontario to Alabama I have never observed ripple-mark in this formation. Prof. Van Ingen informs me that he has noted ripple-mark in the New York Oriskany, but evidently this phenomenon is rare in the Oriskany as compared with many formations. In the Knobstone or Riverdale sandstone of Indiana and Kentucky ripple-mark is equally rare throughout its extended outcrop area. The Kaskaskia sandstone of southern Indiana is also entirely free from ripple-mark so far as I have observed. These sandstone formations without ripple-mark are composed of materials which closely approach the highly ripple-marked beds of other formations in general texture and composition. Scores of other examples might be given of formations in which ripple-mark is either a very rare or a very common feature. The contrast in this particular between different sandstone formations raises the interesting question: why should ripple-mark be a conspicuous feature throughout some sandstone formations and generally absent in others? An explanation of the comparative abundance of ripple-mark in some horizons and its scarcity or absence from others would doubtless go far toward a complete interpretation of the complicated history of the beds discussed. While an adequate explanation may not yet be practicable, a brief consideration of some of the possible reasons for this difference may afford valuable clues to some of the factors in the history of particular formations.

In seeking an explanation of the apparent anomaly of the great abundance of ripple-mark in some sandstone formations and its absence or rarity in others, it is well to remember that the preservation of ripple-mark in marine sands is probably always the result of a special combination of conditions. If the tidal currents which produce asymmetric ripple-mark always flowed with the same strength in successive tides the ripple-mark resulting from each tide would doubtless be always obliterated by the migrating ripples of the succeeding tide. But tidal currents may be interrupted and even completely checked in certain areas by winds or flooded rivers. In the latter case large accessions of sediment from the land, in the temporary absence of the regular tidal current, might result in the ripple-mark of the last tide being covered and permanently preserved under the influence of a current from a flooded river strong enough to check the tidal current but too weak to produce ripple-mark. The flood tidal current is thus sometimes held in abeyance in San Francisco bay. In the Golden Gate the current during spring tide has a maximum velocity of 6 or 7 miles per hour. "At periods of great freshets in the Sacramento and San Joanquin rivers there have been instances of very slight surface current or none at all on the small flood in the Golden Gate."[1] In such a case as this the sediment discharged by the rivers would be likely to bury the ripple-mark formed by the outgoing tidal current and thus protect it from destruction by later current action. It is safe to assume that during the deposition of those sandstones in which ripple-mark is absent such special conditions as these never occurred.

Probably the simplest and most frequently applicable explanation of the presence or absence of ripple-mark in sandstone formation is to be found in the fact that ripple formation depends on current velocity. Dr. Owen[2] finds that in shallow water a current of less than 0·85 feet per second does not move ordinary sea sand. A speed of current between 0·85 and 2·5 feet per second moves the sand in the form of ordinary current ripples. With a current above 2·5 feet per second the sand moves in a sheet without forming ripples. Current velocities between these produce ripple-mark. The absence of current ripple-mark from parts or the whole of a formation would, therefore, suggest that the beds without ripple-mark had been deposited under the influence of a current velocity which was above the

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[1] Coast Pilot, p. 74.

[2] "Experiments on the transporting power of sea currents," Geog. Jour., vol. XXXI, Jan.-June, 1908, pp. 415-420.

critical velocity of 2·5 feet per second. If cross-bedding is found to characterize the beds without ripple-mark it would no doubt denote a current much too strong or too irregular to produce ripple-mark.

In the case of the paucity of ripple-mark in the Oriskany sandstone still another explanation suggests itself. In many places this formation is highly calcareous. In many sections where it is at present a pure sandstone the original calcareous material has been leached out. It appears most probable that the calcareous matter in the sand of this formation would have interfered with ripple-mark development during its deposition and the absence of ripple-mark in many sections can probably be attributed to this calcareous cement.

It seems from my observations that ripple-mark of large amplitude is much more common in limestone than in sandstone horizons. Numerous examples have been cited in other papers[1] of ripple-mark in limestone with an amplitude of one foot or more. J. A. Udden[2] has reported ripple-mark in the Lower Burlington limestone of Iowa having an amplitude of 4 to 6 feet and with crests rising 6 inches above the troughs. Sowerby mentions 3 to 4 inches as the usual width of ripple-mark crests in "medium sandstone" and gives about three-fourths of an inch as the smallest and about one foot the greatest amplitude observed in sandstone. With one exception,[3] in the Medina sandstone, I recall no observation or record of sandstone ripple-mark with amplitude exceeding one foot. The sizes commonly met with are indicated in Plates XXIV to XXIX. The observations recorded in the first part of this paper, however, show that the formation of ripple-mark in sand with an amplitude of several feet is not uncommon. The extreme rarity of such large ripple-mark in sandstone can, therefore, hardly be due to its not having

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[1] E. M. Kindle, "Note on a ripple-marked limestone," Ottawa Naturalist, vol. 26, 1912, pp. 1-3, plate VII.

"A comparison of the Cambrian and Ordovician ripple-mark found at Ottawa, Canada, Jour. Geol., vol. 22, 1914, pp. 703-713.

C. S. Prosser, "Ripple-marks in Ohio limestones," Jour. Geol., vol. XXIV, 1916, pp. 456-475.

[2] Geol. Surv., Iowa, Ann. Rept., vol. XI, 1901, p. 87.

[3] G. K. Gilbert, "Ripple-marks and cross-bedding," Geol. Soc. Am., Bull., vol. X, 1899, pp. 135-140.

been formed while the beds were being deposited. It is probable that these large ripple-marks were more subject to destruction by erosion than the smaller ones, while later deposits of sand were being laid down, or less capable owing to size of being fully uncovered when preserved without partial destruction.

RIPPLE-MARK AS A CRITERION OF MARINE OR LACUSTRINE SEDIMENT.

Since the symmetrical and asymmetrical types of ripple-mark are the product respectively of wave and current action, it is possible to infer from the absence or rarity of one or the other type of ripple-mark in a given series of rippled beds whether they were accumulated under the dominant influence of current or wave action. Current action is nearly everywhere a feature of shallow marine waters, owing to the tides, and it is generally absent or comparatively rare in lakes. Hence the abundance of the wave-made type of ripple-mark in a sandstone formation (Plates XXV, XXVI) and the absence of the asymmetrical type would indicate its formation under lacustrine conditions. The great predominance on the other hand of the asymmetrical type (Plates XXVII, XXIX) of ripple-mark would as certainly suggest the work of tidal current action and marine conditions. Wave action is, of course, as much a feature of marine as it is of lake waters; but, as has been pointed out in the first part of this paper, the product of the joint action of wave and current on sand is invariably the asymmetric ripple, while the entire absence of current action is essential to the formation of the symmetrical ripple.

The Joggins section well illustrates this interpretation of the significance of types of ripple-mark. The Carboniferous section at Joggins, Nova Scotia, was carefully examined with reference to the type of ripple-mark developed in it. The general absence from this section of marine fossils and the marvellous abundance at many horizons of upright tree trunks often holding terrestrial fossils and other land plants can leave no doubt that the sediments in it, with the possible exception of some interpolated marine beds, are of non-marine origin and represent the deposits of a shallow marshy lake probably near and at times connected with the sea. If, as my observations on land and marine ripple-mark appear to indicate, the symmetrical type is generally found on lake bottoms and the asymmetrical type on sea bottoms the first named type of ripple-mark should greatly predominate in the sandstones of the Joggins section. The ripple-mark beds of this section were carefully examined twice along the series of beds extending from the old grindstone quarry to the cliffs southwest of the Joggins mines. Many horizons of finely preserved ripple-mark occur in this famous section (Plates XXV B and XXXII). All of those observed are, with one exception, of the symmetrical type. One slab which had fallen from the cliffs near the middle of the section displayed the asymmetrical type of ripple-mark, probably representing either current action under special conditions within a lacustrine area or temporary access of marine currents. The evidence of the other ripple-mark horizons fully conforms with and corroborates the evidence of the fossils in indicating lacustrine origin for the great bulk of the sediments of the section. The current marks found in this section (Plates XXXI and XXXIII) occur below the Coal Measure series.

The Berea sandstone of Ohio is another terrane which furnishes in its abundantly ripple-marked beds important evidence regarding their history (Plate XXVII). With reference to the type of ripple-mark characterizing these beds Hyde writes[1]: "The ripples are entirely (so far as observed) of the oscillation (symmetrical) type, that is, formed by the slight forward-and-back motion of the water which is caused by the passage of a wave. Not a single occurrence has been noticed which suggests typical 'ripple-drift,' the type of ripple which is produced by strong currents of water moving in one direction. The ripple crests are usually from three to five inches apart and rarely reach six inches. This interval varies within a few feet on any surface." My own observations which include numerous sections of the Berea sandstone between lake Erie and central Kentucky coincide with those of Prof. Hyde in noting no exceptions to the

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[1] Hyde, Jesse E., "The ripples of the Bedford and Berea formations of central and southern Ohio with notes on the palæogeography of that epoch," Journ. Geol., vol. XIX, No. 3, 1911, pp. 262-263.

symmetrical type of ripple-mark in this formation. A specimen of Berea sandstone ripple-mark presented to the Geological Survey by Prof. Prosser shows rounded crests and troughs with an amplitude of $2\frac{3}{4}$ to $3\frac{1}{4}$ inches and maximum elevation of crests of one-fourth inch. It appears safe to conclude in view of the absence of asymmetrical ripple-mark in the Berea that it represents a lacustrine deposit. Some of Prof. Prosser's[1] careful descriptions of the ripple-mark and closely associated sun-cracks in this horizon can only be interpreted as indicating very shallow water in this lake which at times over the shallower parts entirely disappeared. Prosser states: "The coarser layers of sandstone have numerous examples of small ripple-marks with the crests from 1 to 2 inches apart. The shale shows splendid examples of sun-cracks, extending almost to the very base of the zone, some of which have fillings an inch in width." Ripple-marks with an amplitude of 1 inch would certainly indicate water not many inches in depth (see page 28.) while the sun cracks, of course, show temporary desiccation. This association of ripple-mark of small amplitude and mud-crack in the same set of beds confirms the inference of very shallow water conditions, an inference that would be drawn from the ripple-mark alone.

The evidence for the lacustrine or continental origin of the Berea sandstone furnished by the fossils, though somewhat inconclusive when taken alone, points toward their non-marine origin. Several fragments of fish remains have been found in some of the Berea sandstone quarries. These afford little or no evidence regarding their affinities to marine or freshwater types. Other fossils are unknown in it in Ohio, although its supposed equivalent, the Cory sandstone of Pennsylvania, carries a marine fauna of Pennsylvanian age. The absence of invertebrate fossils from this horizon in Ohio is itself evidence of some bar to their existence in the waters in which the Berea sandstone was laid down and the evidence of the ripple-mark leads to the conclusion that this bar was the fresh water of a shallow lake. The Berea sandstone is considered by Girty, Prosser, Kindle, and others to represent the initial formation of the Carboniferous in

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[1] Bull. Geol. Surv., Ohio, No. 15, pp. 250, 266-7.

Ohio. It has been shown by Prosser,[1] Cushing,[2] and others to be separated from the Bedford formation below it by an unconformity. It may be regarded as representing the lacustrine or lagoonal conditions which initiated the Carboniferous period in northern Ohio.

There are other formations in which the evidence of ripple-mark, with reference to marine or continental conditions, is not so clear. In the Potsdam sandstone of Ontario and New York, for example, the ripple-mark evidence does not admit of such easy interpretation as in the Berea sandstone. Both symmetrical and asymmetrical ripple-mark (Plates XXV A and XXVII A) are found in the sections which I have examined. In the South March section west of Ottawa 35 or 40 feet of this sandstone are exposed. In the lower 10 feet of the section *Lingulepis acuminata* Con. and *Scolithus canadensis* are abundant fossils. In the higher beds, however, fossils of any kind appear to be entirely absent, while ripple-mark which has not been noted in the fossiliferous beds appears. Both the symmetric and asymmetric types are present. The former seems to be more common than the latter. It is perhaps not safe to offer any positive opinion regarding the inferences to be drawn from the presence of the two types of ripple-mark in closely associated beds. The facts noted appear to suggest, however, that most of the Potsdam beds originated under non-marine conditions.

The numerous beds of symmetrical ripple-mark which are so common in the Potsdam could not possibly have been produced by tidal currents. If these beds were chiefly marine sediments and if their sands had been subjected to the action of tidal currents asymmetrical ripples should greatly predominate over the symmetric type. The symmetric type, however, appears to be the dominant form and the presence of the asymmetrical ripples seems to be most easily explained as the result of lake currents or of tidal currents representing occasional marine connexion with lagoonal waters. The entire absence of marine fossils from most sections of the Potsdam in Ontario and the presence in others of fossil trails which have not been correlated

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[1] Geol. Surv., Ohio, Bull. 15, 1912, pp. 105, 252.

[2] Bull. Geol. Soc. Am., vol. 26, 1915, p. 155.

with any species known in the marine facies points strongly toward the absence of marine conditions and tends to confirm the interpretation of the evidence of the ripple-mark given above.

Considerable interest attaches to the history of the Edmonton beds of Alberta because of the numerous specimens of unique vertebrate fossils which have been found in them. The fresh-water fossils found in these beds clearly indicate their continental origin. But the fossils afford no definite evidence as to whether the beds are of fluvial or lacustrine origin. Some of the thin sandstone beds of this formation are beautifully ripple-marked. The character of this ripple-mark should indicate whether it is the product of current or wave action; if the former origin is indicated we may infer that it was formed on the bed of a river; if the latter we may conclude that it originated on a lake bottom. Examination of a very fine slab of this ripple-mark which was collected by Geo. Sternberg and of photographs made in the field by Mr. Sternberg clearly indicate the symmetric type of ripple-mark. This is shown in Plate XXIV. The slab examined was collected 2 miles above Tolman ferry, Red Deer river, Alberta, in tp. 33, range 22. The ripple-mark shows gently rounded troughs and sharp angular crests spaced, where simple, $\frac{7}{8}$ to $1\frac{1}{8}$ inches apart. The troughs have a depth of $\frac{1}{6}$ to $\frac{1}{8}$ inch. Parts of the ripple-mark pattern show a small secondary ridge in the middle of the troughs rising $\frac{1}{16}$ of an inch. The ripple-mark with a mid-ridge has the main ridges spaced at $1\frac{1}{8}$ to $1\frac{1}{4}$ inches. The distinct symmetry of this ripple-mark clearly stamps it as of wave origin; and its extremely small amplitude almost certainly indicates its formation under water not more than 1 or 2 feet in depth. It was, therefore, evidently formed beyond the influence of any river current, probably in the shallow water of a marshy lake. Mr. Barnum Brown[1] gives the following description of this locality: "At a point 2 miles above Tolman ferry on the left bank there is a bed 100 yards square, and in which four successive series of ripples are preserved one above the other. Each series was evidently formed by cur-

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[1] Bull. Geol. Soc. Am., vol. 25, 1914, pp. 365-366.

rents coming to the shore line from a different angle as no two are parallel. On one of the slabs collected there are worm tracks and several impressions of a horse-tail rush." As already stated the symmetry of these ripple-marks shows that they are not current but wave made. Mr. Brown would have been correct if he had stated that they indicate winds of varying direction rather than currents.

At other levels in these beds asymmetrical ripple-mark has been found by Mr. Sternberg which indicate current action.

PALÆOGEOGRAPHIC SIGNIFICANCE OF RIPPLE-MARK.

In formations which are very generally ripple-marked throughout careful tabulation of the general trend of the ripple-mark may afford important evidence regarding the position of shore-lines at the time of their formation. Symmetric or wave-made ripple-mark if found in water of moderate or slight depth will trend approximately with the shore off which it was formed. Asymmetric or current ripple-mark (Plates XXVII to XXIX) will trend at right angles to the course of the current which produced it. In the case of tidal currents the direction of the current is generally parallel to the nearest shore. Hence the asymmetrical ripple-mark produced by them trend at right angles to adjacent shore-lines. Fossil asymmetrical ripples thus indicate a shore-line trending at right angles to their course while symmetrical ripples indicate a shore-line parallel to their own direction. It is, of course, evident that any trustworthy deductions of this kind must be based upon a large number of observations.

Prof. Jesse E. Hyde has made effective use of this kind of evidence in his study of the ripple-mark in the Bedford and Berea formations. His deductions regarding the trend of the shore-line, based upon the observed constancy of direction of the ripple-mark, are indicated in the following extract from his paper:[1] "The conclusion seems to be warranted that the persistency of direction of the ripples of the Bedford and Berea indicates the prevailing direction of the water waves which formed them and that this in turn was controlled, either by a shore line or water so shallow as to bring the waves into adjustment parallel to this

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[1] Jour. Geol., vol. XIX, No. 3, April-May 1911, p. 265.

shore line, or, if it was only shallow water control, to the contours on the sea floor....This shore line or the contour of the bottom must have been parallel to the ripple direction, that is, it must have extended in a northwest southeast direction." Hyde's conclusions regarding the trend of the shore-line seem unassailable from the evidence of the ripple-mark presented. But no direct evidence as to whether the shore-line was east or west from the area studied can be derived from the ripple-mark. Prof. Hyde's conclusions that the Berea shore-line lay to the southward is based upon other considerations than the ripple-mark evidence. In this conclusion I do not concur, but this point is not material to the present discussion and need not be pursued here.

ORDER OF SUCCESSION INDICATED BY RIPPLE-MARK.

In areas of excessive orogenic disturbances it is often very difficult to ascertain with certainty the original order of superposition of the beds. The discovery in such beds of ripple-mark often serves to clearly indicate which is the top and which is the bottom of the section. A reversed or overturned bed of ripple-mark would, of course, indicate a corresponding reversal of the original order of the beds of the section. This use of ripple-mark in determining order of superposition, of course, assumes that the trough and crest in ripple-mark are unlike and distinguishable. Certain kinds of ripple-mark which have ridges and troughs distinctly unlike may be used in this way. Where the crest and trough show a similar degree of curvature as in the case of some wave-made ripple-mark it would be impossible to distinguish the sandstone mould from the original ripple-mark. Most examples of current made ripple-mark exhibit the same characteristic, the contour of the trough and crest being so nearly identical that discrimination between a mould and the original would be very difficult and often impossible in the case of fossil ripple-mark in beds where the order of superposition was unknown. This will be clearly seen by reference to the ripple-mark profiles in Figures 3 and 7 H and I. If the top and bottom of figures 3 E and 3 F or 7 H and 7 I be reversed the figures will show nearly the same contours for the tops of the ridges as before reversing. It is, therefore, evident that current ripple-mark and wave ripple-mark with crests and troughs of similar contour cannot be used as criteria for determining the true order of superposition in areas of complex structure. The type of ripple-mark, which is very common in wave ripple-mark, characterized by sharp angular crests separated by wide rounded troughs (Figure 7 C, D, and G) or rounded hollows, each of which has a low sharp ridge in the centre (Figures 4 C and D and 7B) may be depended upon, however, to furnish decisive evidence regarding the order of superposition in disturbed areas. There appears to be no exception to the rule that in the type of ripple-mark in which the profile shows a series of gentle curves connected by angles the angles will represent the crests. Mr. G. K. Gilbert's[1] observations on this point coincide with my own. Since no examples of ripple-marks with rounded crests and angular troughs are known, the angular parts of the profile can be considered to represent the crests when found in beds whose order of superposition is unknown. While the evidence of this kind of ripple-mark is entirely trustworthy it should be clearly understood that the interpretation of the evidence of the other types referred to is difficult and generally of no value. Prof. Van Hise[2] pointed out some years ago the utility of ripple-mark in determining order of superposition, but neither he nor Jukes nor Geikie,[3] who discussed this principle, indicated that many varieties cannot be used in this way.

Cross Bedding.

Cross bedding represents in many instances one phase of a phenomenon called sand waves which are nothing more than current made ripple-mark of mammoth porportions that appear to be formed instead of ripple-mark when the current is overloaded with sediment. The crests are often 15 to 35 feet apart and rise 2 to 3 feet above the troughs. They are formed on the beds of most streams which are heavily laden with sediment and along most coast lines which are subject to the action of powerful

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[1] Bull. Phil. Soc. of Wash., vol. 2, 1874-78, pp. 61-62.

[2] 16th Ann. Rept. Direct U. S. Geol. Survey, Pt. I, 1896, pp. 719-721.

[3] Student's manual of geology, 3d. ed. 1871, p. 63.

tidal currents. A set of beds which have been laid down in a zone characterized by sand-wave formation may not preserve the outlines of any single set of sand waves but the steep foreset beds which are formed as these waves travel with the current will be preserved as the familiar cross bedding so common in many coarse sandstones. Cross bedding is thus characteristic of both river and tidal current laid beds. The direction of the inclined beds in the river deposits should, however, possess a degree of uniformity not shared by those which have been produced in marine deposits under the influence of a current which daily reverses its direction. The variable direction of the cross bedding in marine clastics should serve to distinguish them from continental river laid beds.

Cross bedding on a much finer and smaller scale than that developed in connexion with sand waves may characterize sandstones formed under water velocities suitable for the formation of ordinary asymmetrical ripple-mark. J. E. Spurr[1] and T. A. Jagger, jun.,[2] who held different views of the subject, have very fully discussed this type of structure.

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[1] Spurr, J. E. "False bedding in stratified drift deposits," Am. Geol., vol. XIII, 1894, pp. 43-47. "Oscillation and single-current ripple-marks," Am. Geol., vol. XIII, 1894, pp. 201-206.

[2] Jagger, T. A., jun., "Some conditions of ripple-mark," Am. Geol., vol. XIII, 1894, pp. 199-201.

C

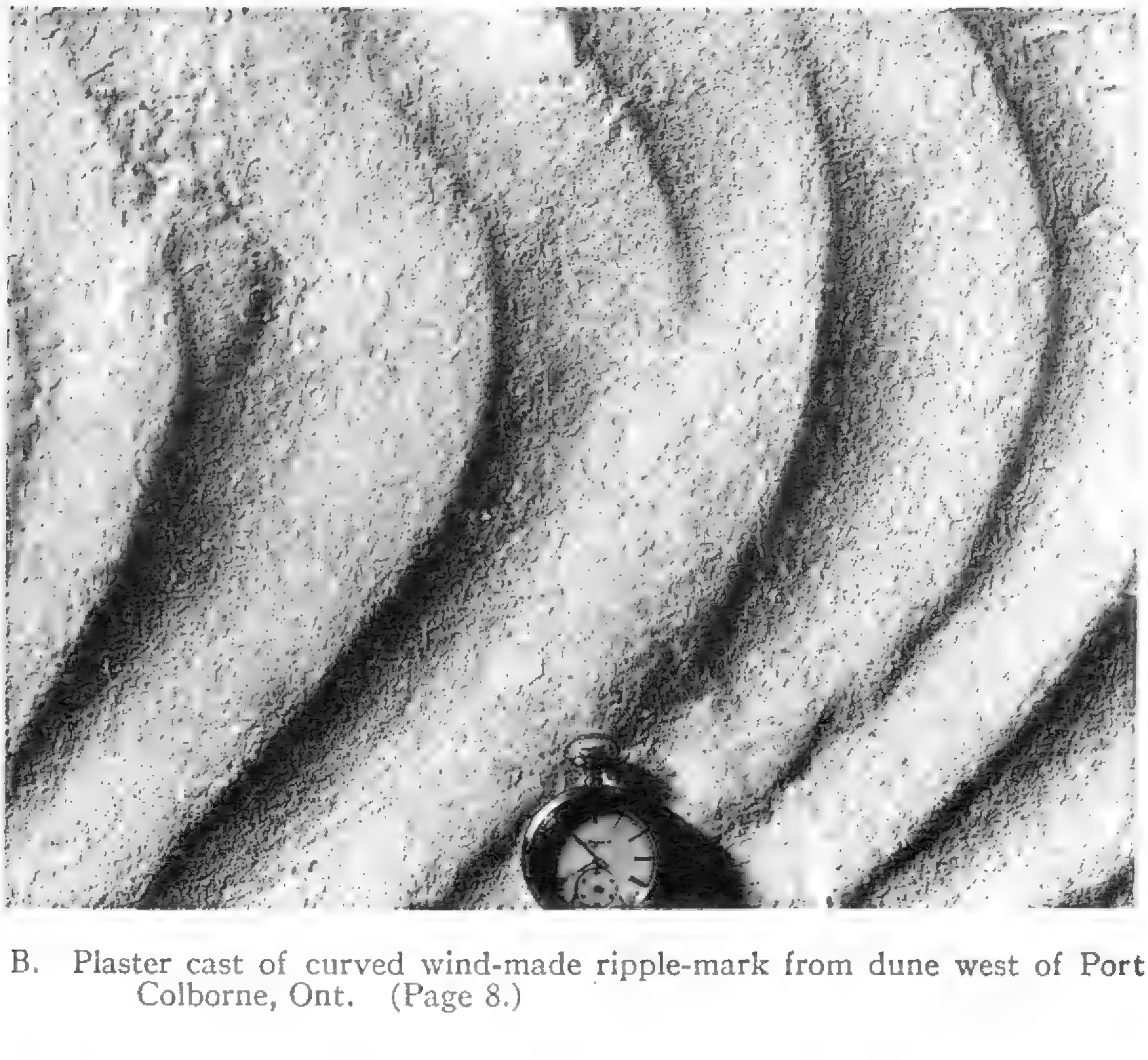
A. Ripple-mark on a sand dune near Wellington, Ont.

B. Ripple-mark and wind excavation around a stump on sand dune near Wellington, Ont.

C. Margin of an advancing dune showing sand at angle of rest; the house is now (April, 1916) partially buried; photo taken July 9, 1914; Sand Bank, Ont.

(Pages 8, 9.)

A. Plaster cast of wind-made ripple-mark from dune near Wellington, Ont. (Page 8.)



B. Plaster cast of curved wind-made ripple-mark from dune west of Port Colborne, Ont. (Page 8.)

A. Brook with rippled surface flowing over sand plain, showing appearance of the surface when ripple-mark is being formed on sand under shallow stream. (Page 12.)

B. View on Grass river, New York, showing ripple-mark on left side and small terraces in middle of picture, left by falling stream. Photo by Orra P. Phelps. (Page 18.)

A. Brook flowing over sand and forming ripple-mark and current mark of irregular pattern, under the two curving lines of dimples, Hemlock lake, Ottawa. (Pages 13, 37.)

B. Profile view of brook shown in A. (Page 13.)

A and B. The bore ascending the Petitcodiac river at the turn of the tide, Moncton, N.B. (Page 19.)

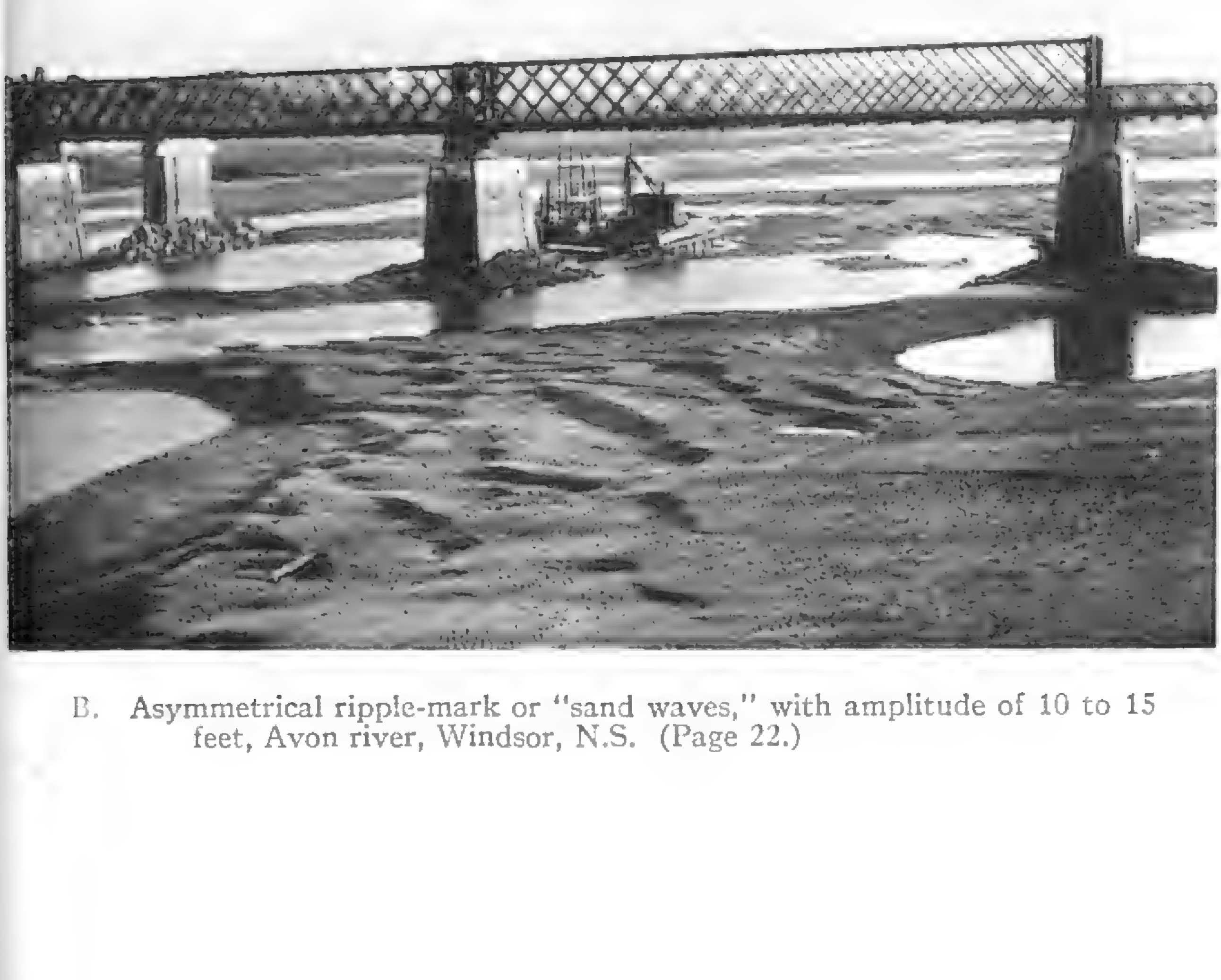
A. High tide in bay of Fundy at Port Lorne, N.S. (Page 19.)

B. Low tide in bay of Fundy at Port Lorne, N.S. (Page 19.)

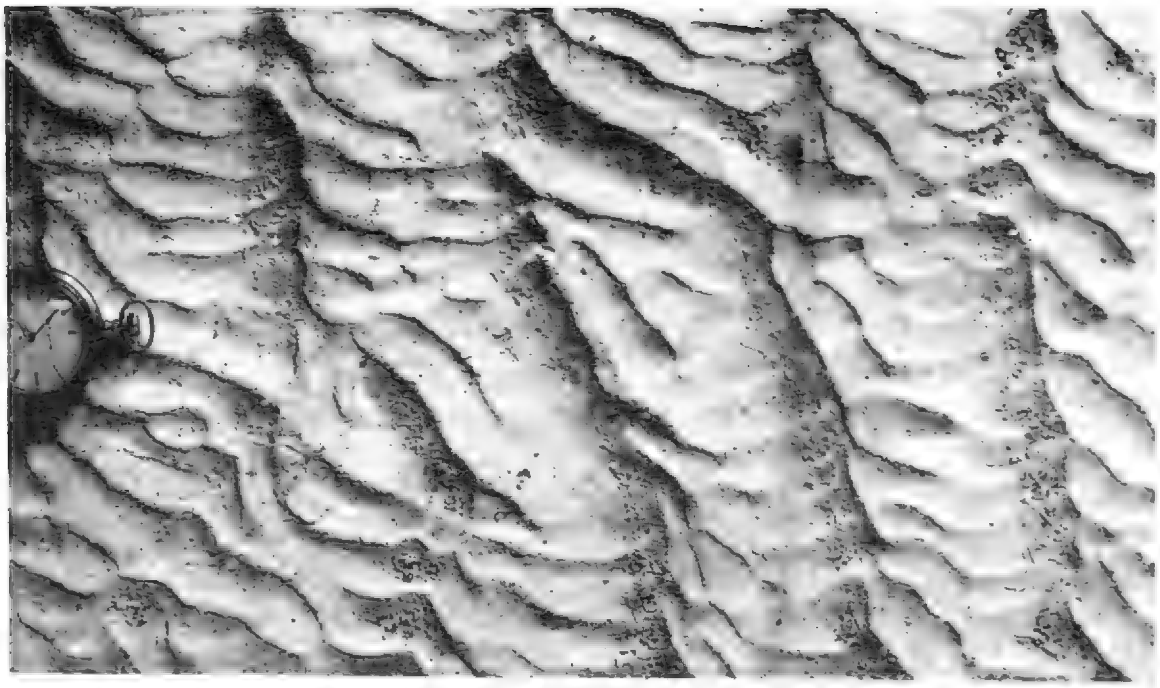
A. Asymmetrical or current ripple-mark left by ebbing tide, current direction from right to left, Windsor, N.S. (Pages 3, 12, 19, 22.)

B. Asymmetrical ripple-mark, current direction from left to right, Windsor, N.S. (Pages 3, 12, 19, 22.)

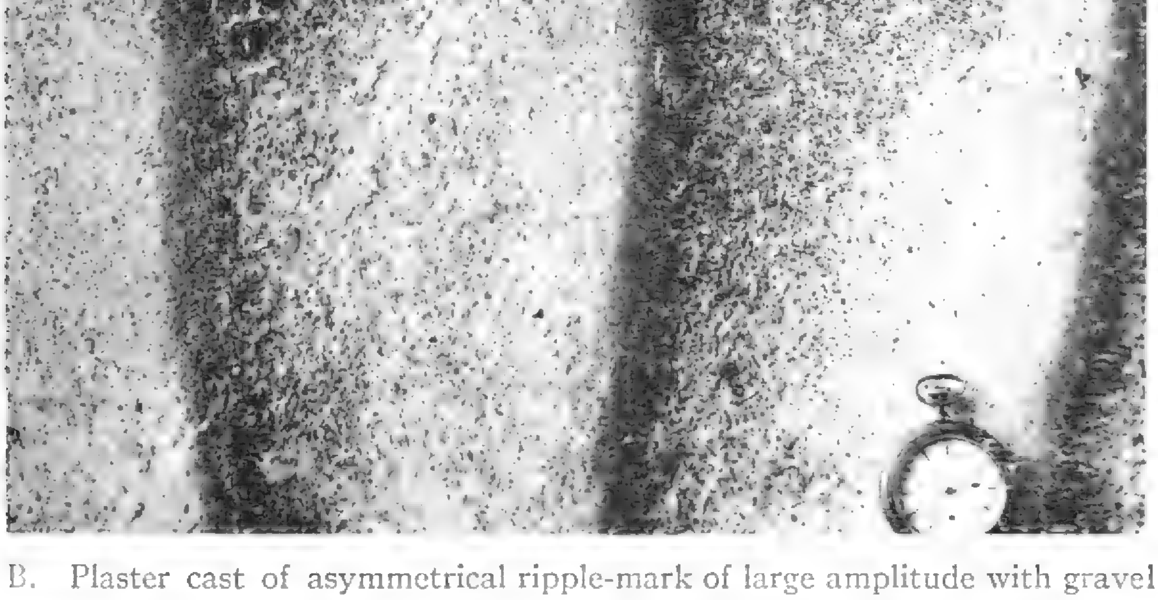
A. Asymmetrical ripple-mark with amplitude of 2 to 4 feet, at the mouth of a tidal stream, northwest corner St. Mary bay, N.S. (Page 19.)



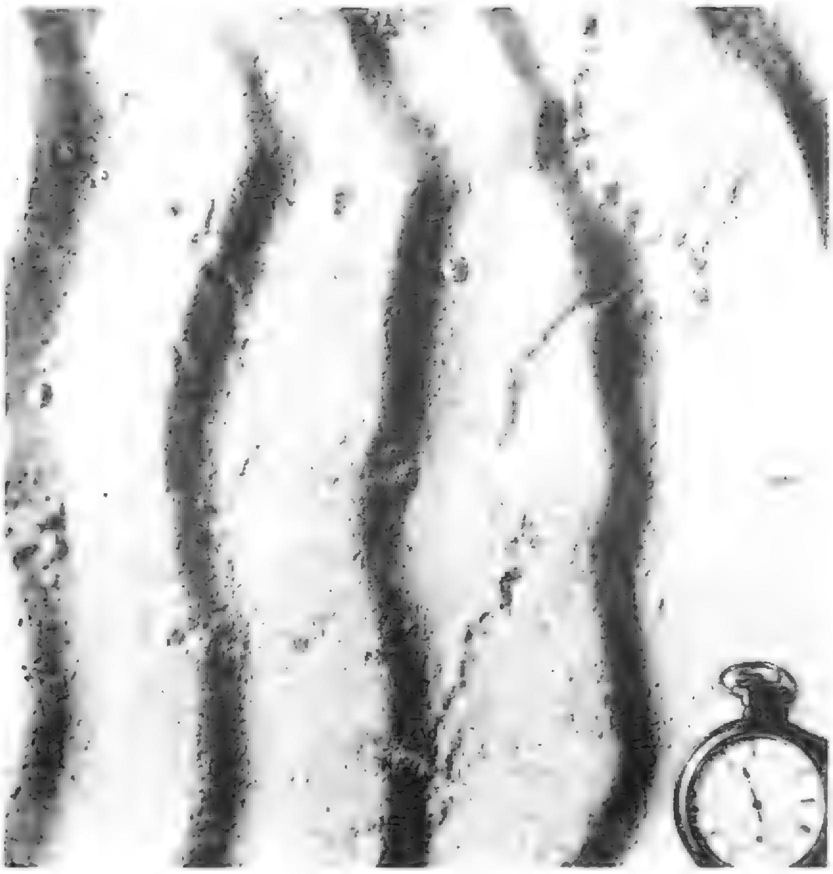
B. Asymmetrical ripple-mark or "sand waves," with amplitude of 10 to 15 feet, Avon river, Windsor, N.S. (Page 22.)



A. Asymmetrical or current ripple-mark modified by waves running oblique to the direction of the current; the finer sculpturing is the work of wave action; Avon river below Windsor, N.S. (Pages 29, 30.)

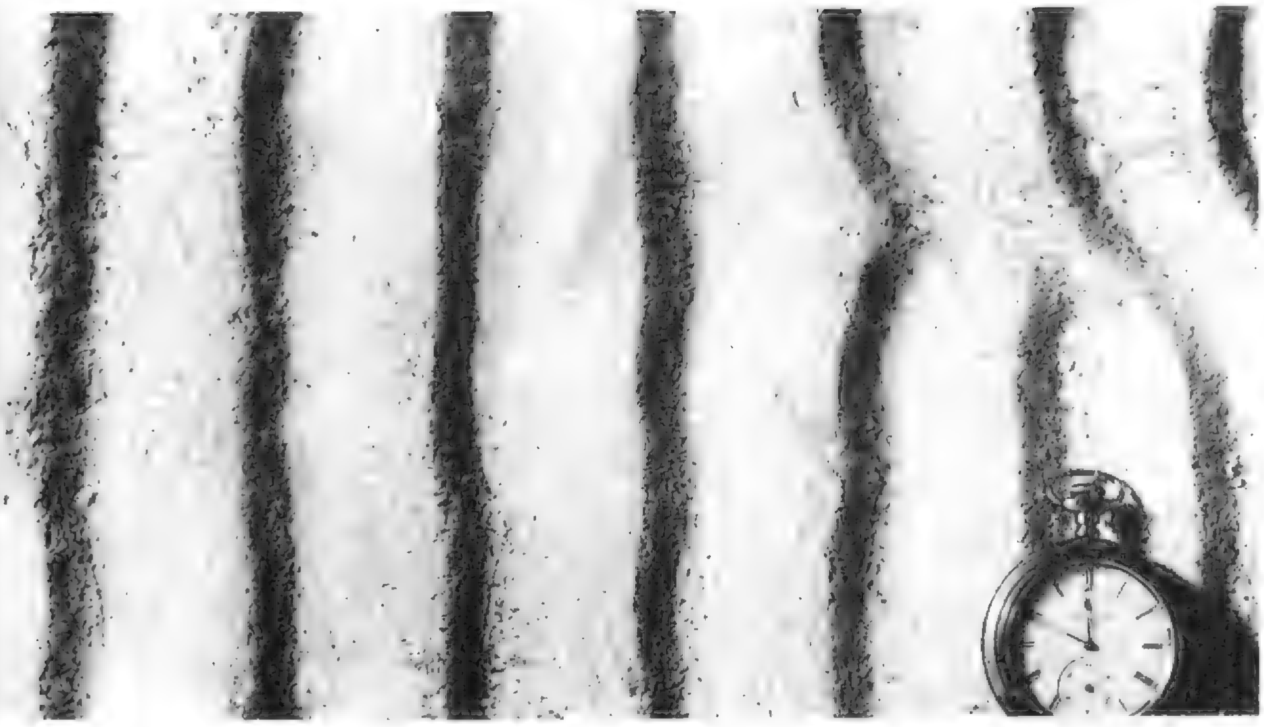


B. Plaster cast of asymmetrical ripple-mark of large amplitude with gravel and coarse sand in troughs, beach at Kingsport, N.S. (Page 21.)



A. Plaster cast of asymmetrical ripple-mark with tracks of invertebrates, Windsor, N.S. (Page 12.)

B. Plaster cast of asymmetrical ripple-mark and invertebrate trails on sand mixed with a percentage of mud, Avon river, Windsor, N.S. (Page 12.)



A. Plaster cast showing detail of asymmetrical ripple-mark made by river current, bed of St. Lawrence river, at Lanoraie, Que. (Page 12.)

B. Plaster cast showing asymmetrical ripple-mark formed by river current, bed of St. Lawrence river at Lanoraie, Que. (Page 12.)

A. Asymmetrical ripple-mark of irregular pattern, Kingsport, N.S. (Page 12.)

B. Asymmetrical ripple-mark interrupted by small boulders; estuary at low tide of Columbia river near Ilwaco, Washington. Photograph by G. K. Gilbert, U.S.G.S. (Page 12.)

A. Irregular basin structure developed in sand by powerful tidal currents, Avon river, N.S., above Canadian Pacific Railway bridge. (Page 22.)

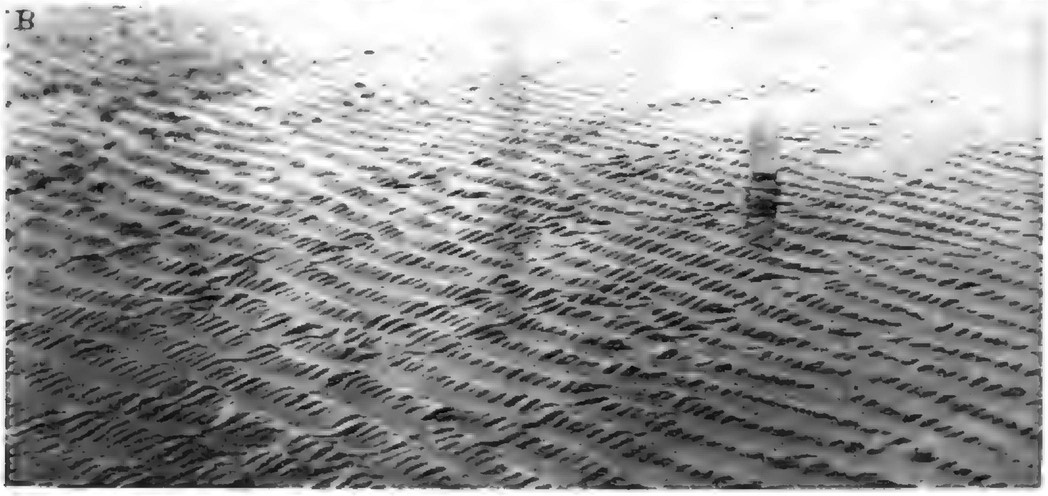
B. Scalloped and terraced beds of sand developed by currents of ebbing tide in zone adjacent to "sand waves" (Plate VII B), Avon river N.S., above Canadian Pacific Railway bridge. (Page 22.)

A. Ripple-mark of irregular pattern resulting from junction of incoming waves and ebb current; view on spit looking toward E, Figure 5, Annisquam, Mass. (Page 32.) Photograph by G. K. Gilbert.

B. Imbricated ripple-mark resulting from converging waves and tidal currents looking in direction opposite to that in A, Annisquam, Mass. (Page 32.) Photograph by G. K. Gilbert.

PLATE XV.

A



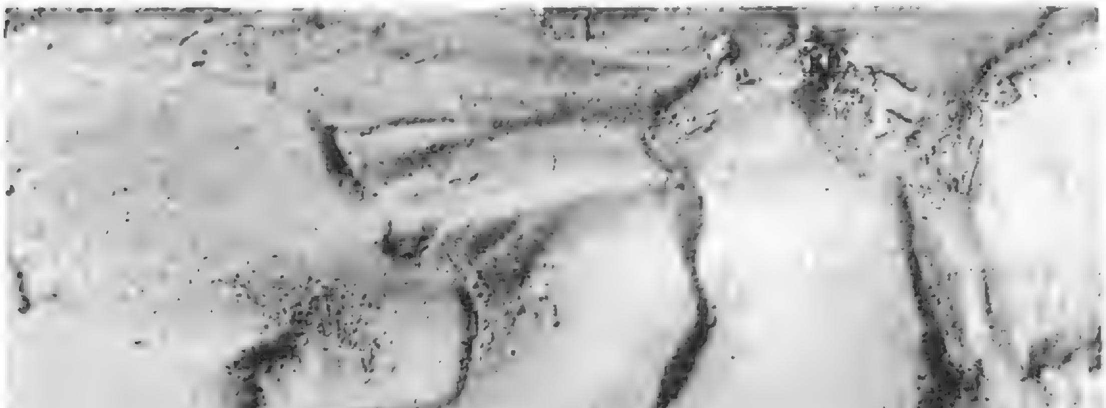
A. Current ripple-mark with fine cross ripples developed by waves running at right angles to the current, Avon river, below Windsor, N.B.

B. Current ripple-mark with transverse wave ripple-mark developed further than in A, Avon river, below Windsor, N.S.

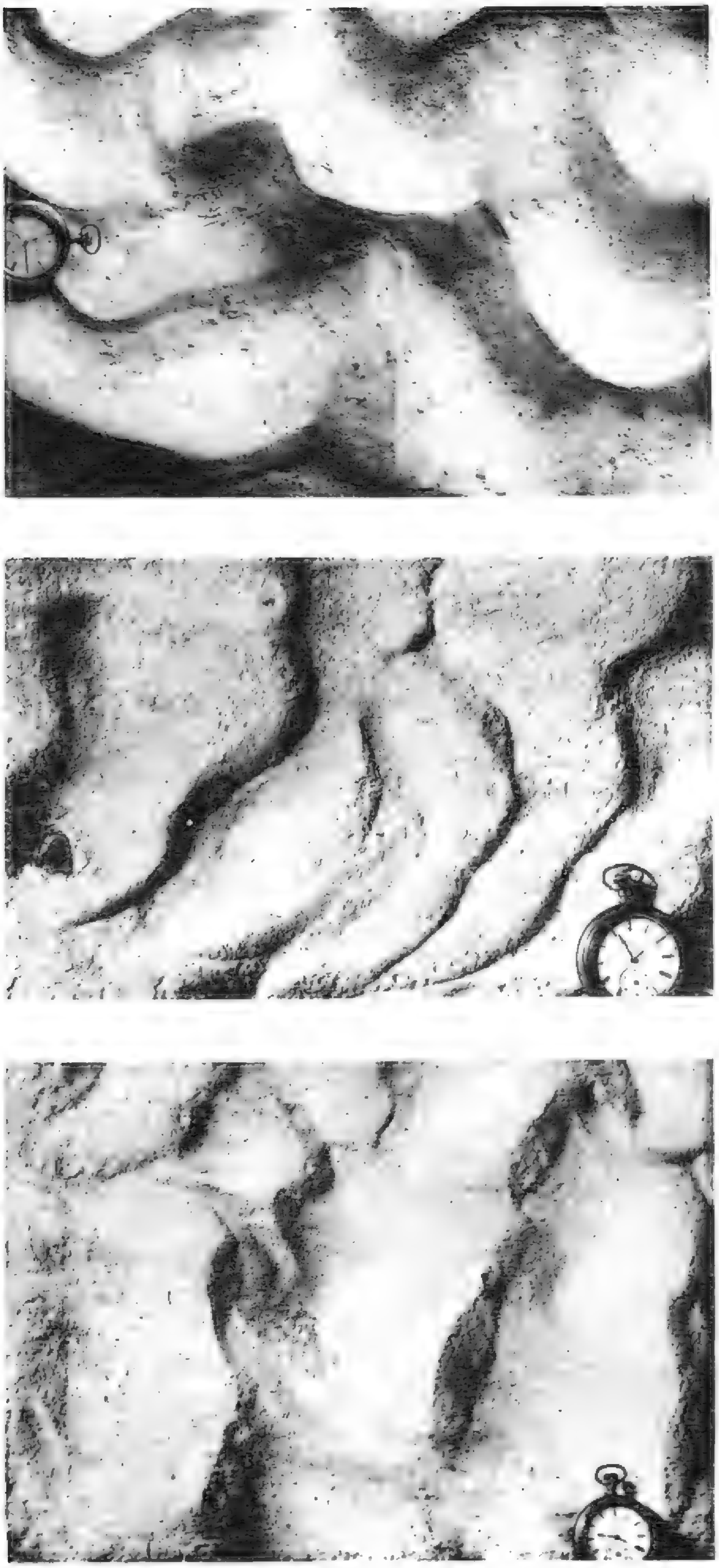
C. Current ripple-mark altered to rows of irregular knobs by wave action transverse to direction of current, Avon river, below Windsor, N.S.

(Page 30.)

A. Plaster cast of miniature delta formed by ebbing tidal current and associated with ripple-mark, Kingsport, N.S. (Pages 36, 37.)

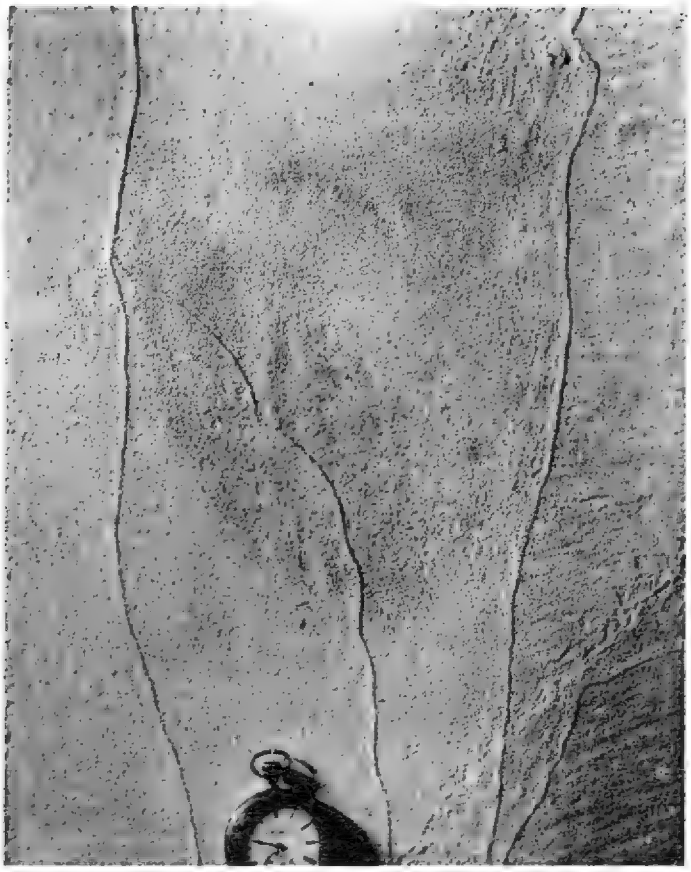


B. Plaster cast of current mark, middle ground bar, mouth of Avon river N.S. (Page 37.)



A, B, and C. Plaster casts of types of current mark. A is the result of tida current action, while B and C represent the work of the current of a small brook. (Pages 36, 37.)

Surf on sandy beach; wave marks (Plate XIX) are formed by the outer fringe of the spent wave which is seen in front of the oxen; Lockeport beach, N.S. (Page 24.)

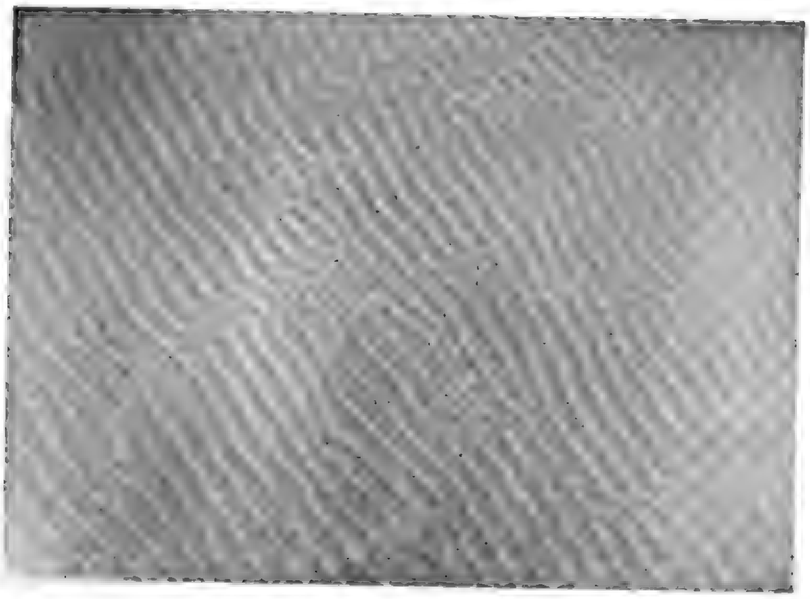


A. Plaster cast of wave marks left by retiring waves, showing fine lines of sand left by four successive waves, shore of lake Erie. (Page 24.)

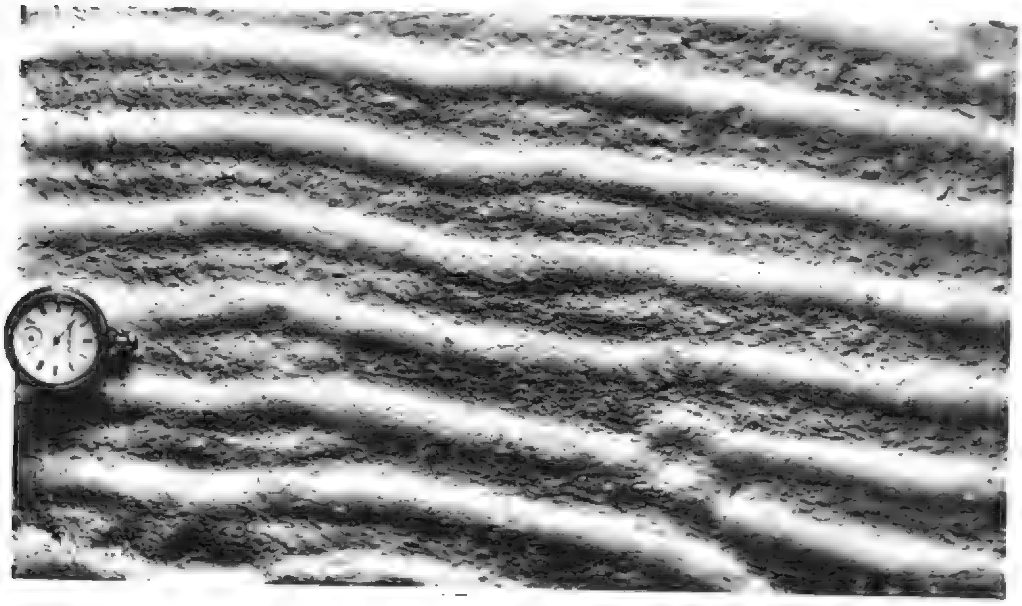
B. Plaster cast of imbricated wave sculpture formed at the margin of the beach by waves crossing a miniature spit, beach of lake Erie at Port Colborne, Ont. (Page 34.)

A. Symmetrical ripple-mark forming under wave action, Wellington, Ont. (Page 24.)

B. Symmetrical ripple-mark under about 6 inches of water with slightly rippled surface, West lake, Wellington, Ont. (Pages 24, 25.)



A. Symmetrical ripple-mark formed by wave action, under 4 inches of water, and photographed through water, Aylmer, Que.

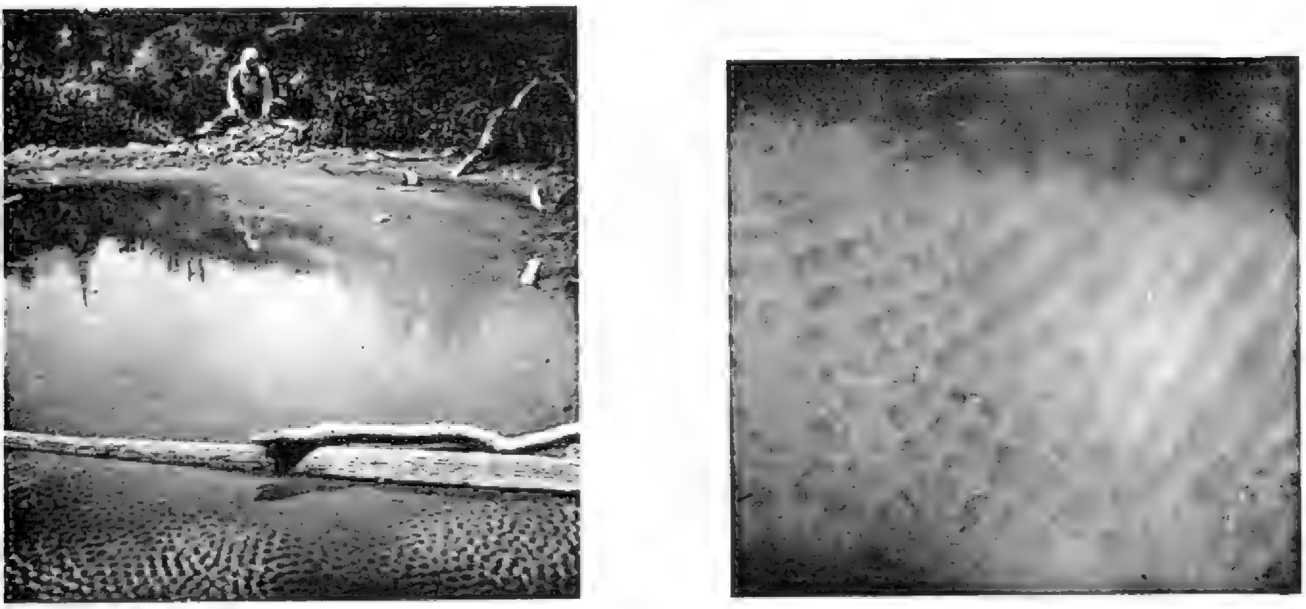


B. Plaster cast of symmetrical ripple-mark with rounded ridges, formed by wave action, under 4 inches of water, Aylmer, Que.

C. Plaster cast of symmetrical ripple-mark with angular ridges, from cast taken at a depth of 6 feet, lake Ontario near Wellington.

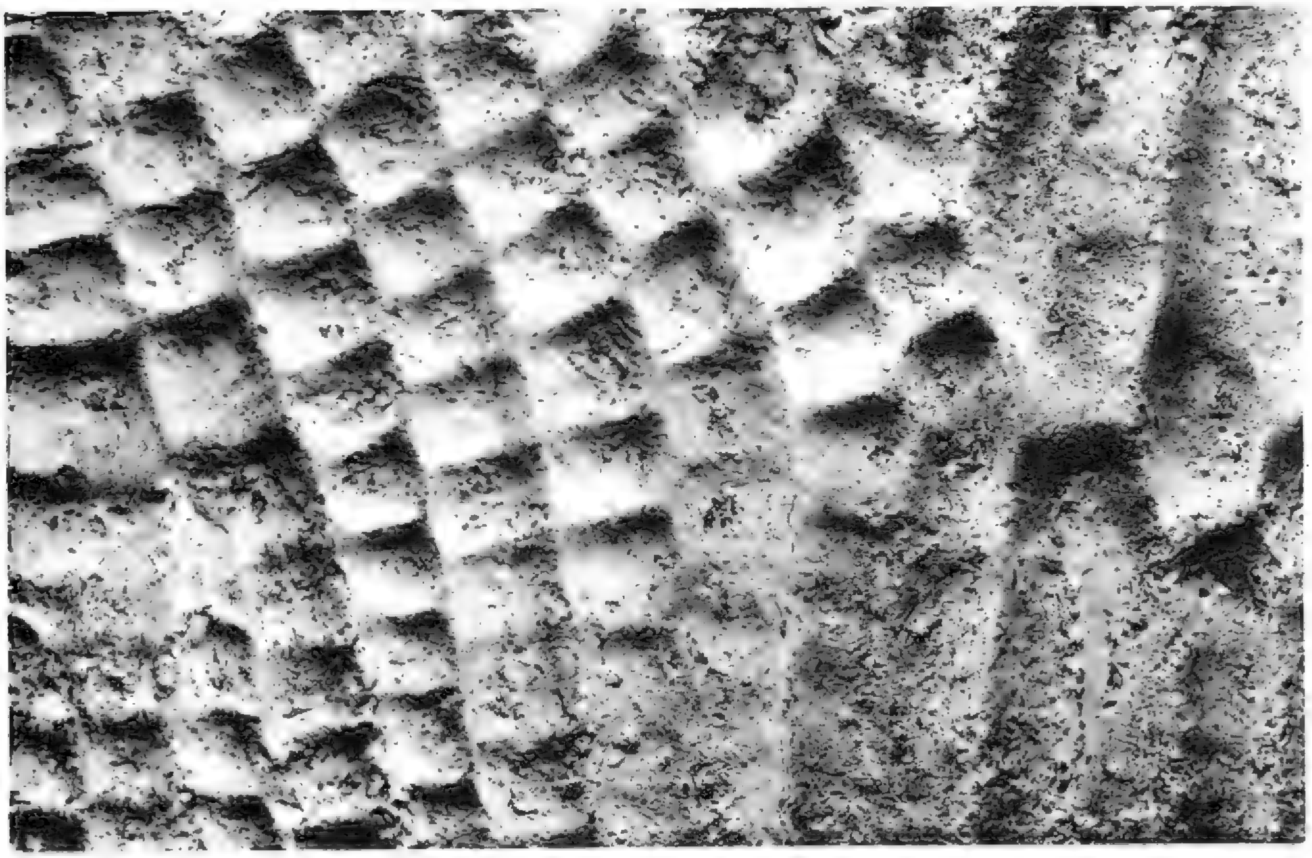
(Pages 23, 24.)

A. Plaster cast of interference ripple-mark showing cells giving way to ordinary ripple-mark in lower right hand corner, lake Deschenes, Ont. (Pages 34, 35.)

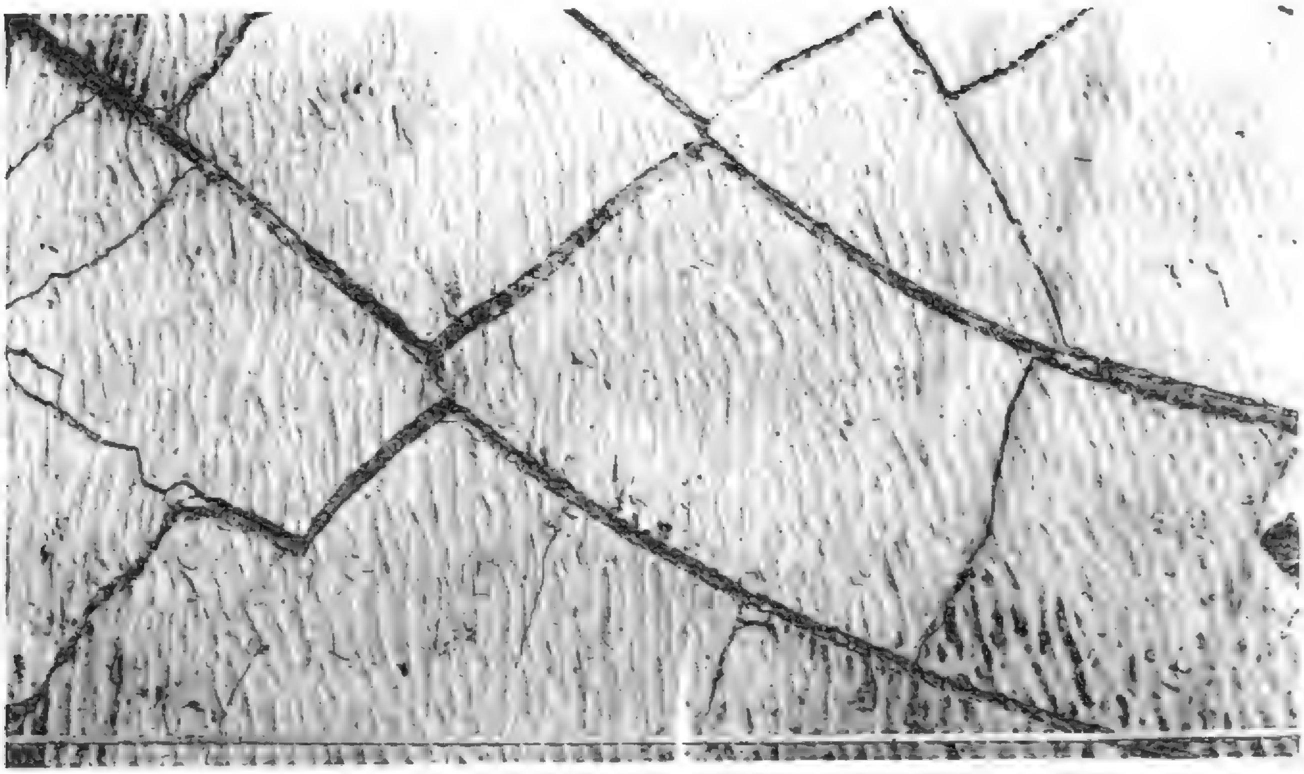


A. Interference ripple-mark in a shallow pond, Hamilton county, Ind. (Pages 34, 36.)

B. Interference ripple-mark photographed in shallow water, Britannia, Ont. Photograph by L. D. Burling. (Page 34.)

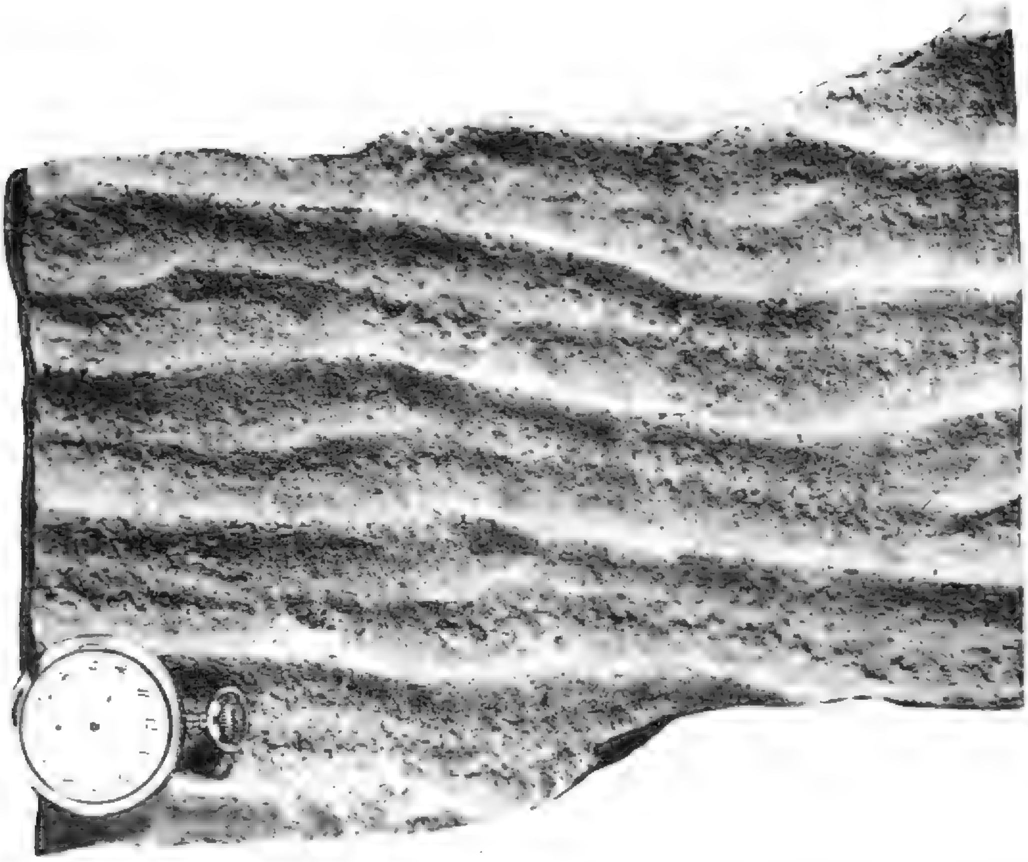


C. Plaster cast, taken under water, of interference ripple-mark, Britannia, Ont. (Pages 34, 35.)



A. Symmetrical ripple-mark cut by joints in Cretaceous sandstone, Edmonton formation, Red Deer river, Alberta. Photograph by Geo. Sternberg. (Pages 43, 52.)

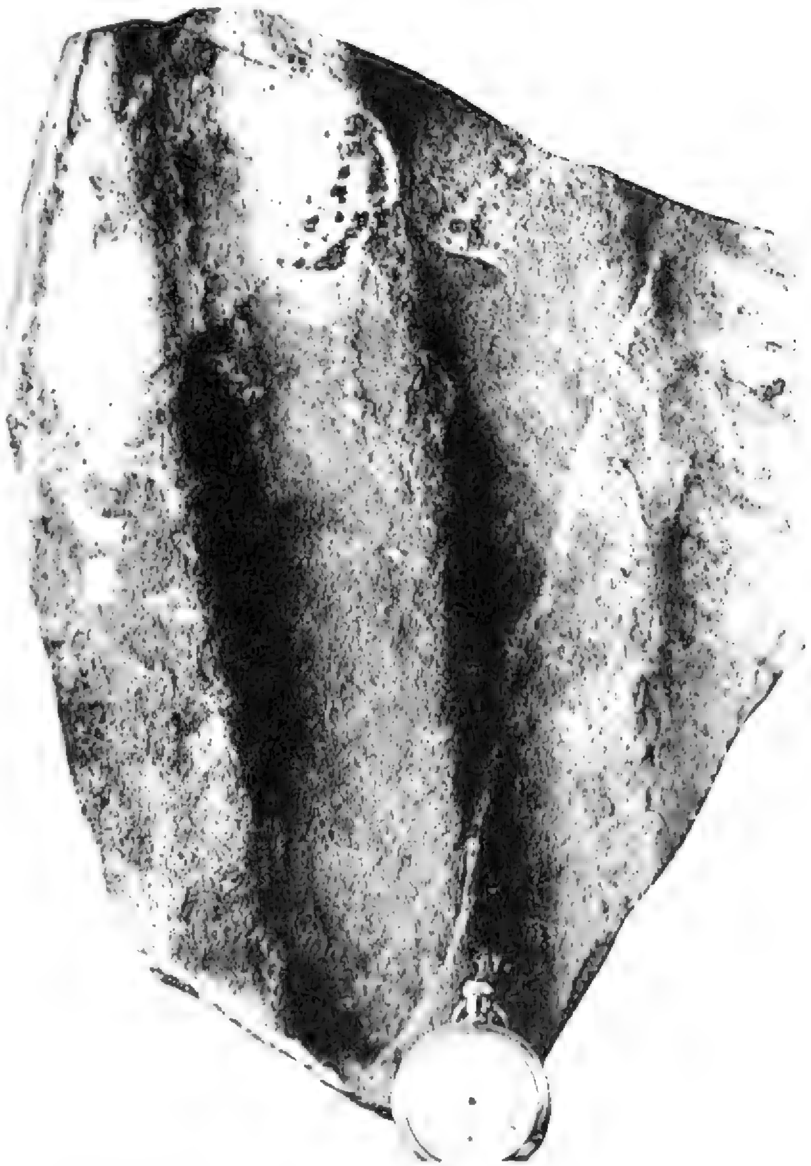
B. View of shale series in which ripple-mark shown in A occurs; the man is standing on the ripple-mark bed; thin seams of coal occur just under the arrows; Edmonton formation; Red Deer river, Alberta. Photograph by Geo. Sternberg. (Page 52.)



A. Symmetrical ripple-mark with small median ridges between much stronger angular ridges on Cambrian sandstone, Hammond, N.Y. (Pages 43, 51.)

B. Symmetrical ripple-mark with sharply angular ridges, Coal Measures, Joggins, N.S. (Page 49.)

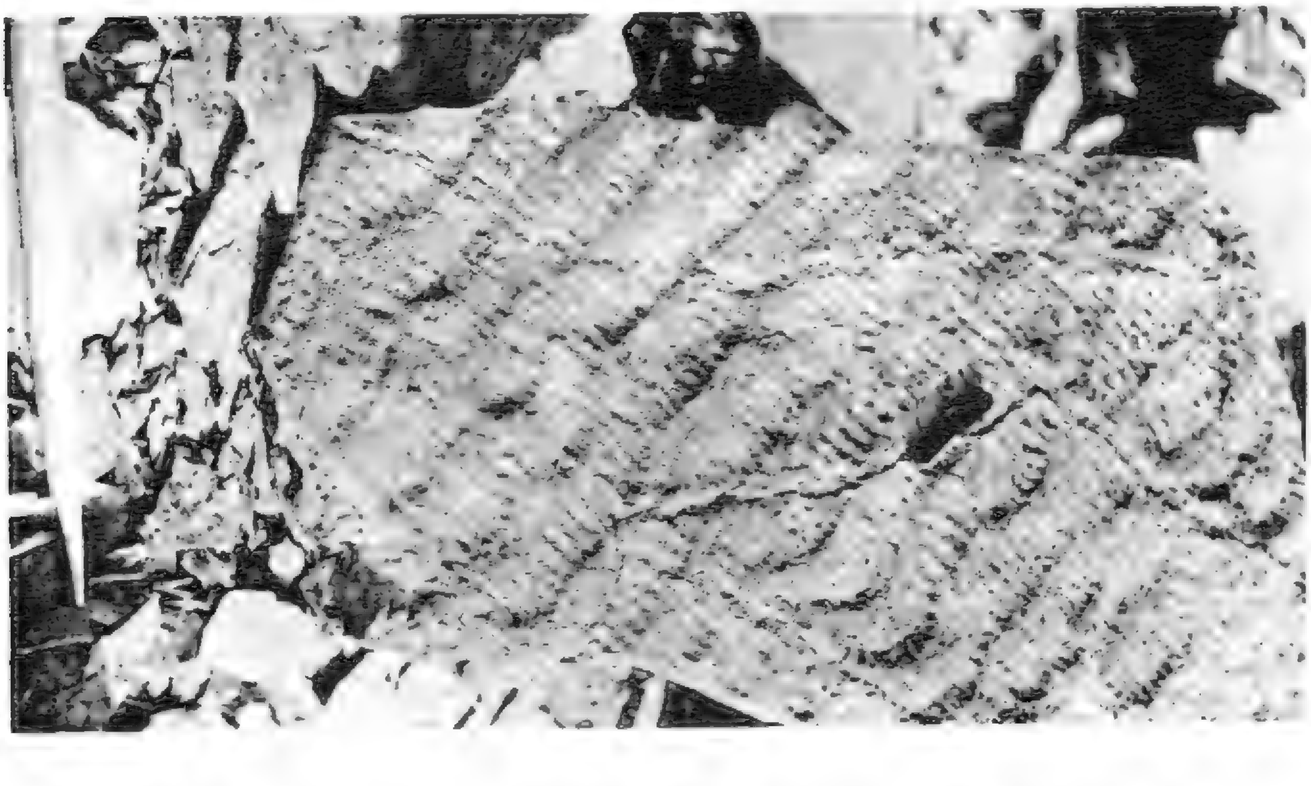
Symmetrical ripple-mark with rounded ridges and traces of diagonal ripple pattern in the troughs, Berea sandstone, Berea, Ohio. Photograph by G. K. Gilbert, U.S.G.S. (Pages 43, 49.)



A. Asymmetrical or current ripple-mark on Cambrian sandstone, South March, Ont. (Pages 43, 51, 53.)

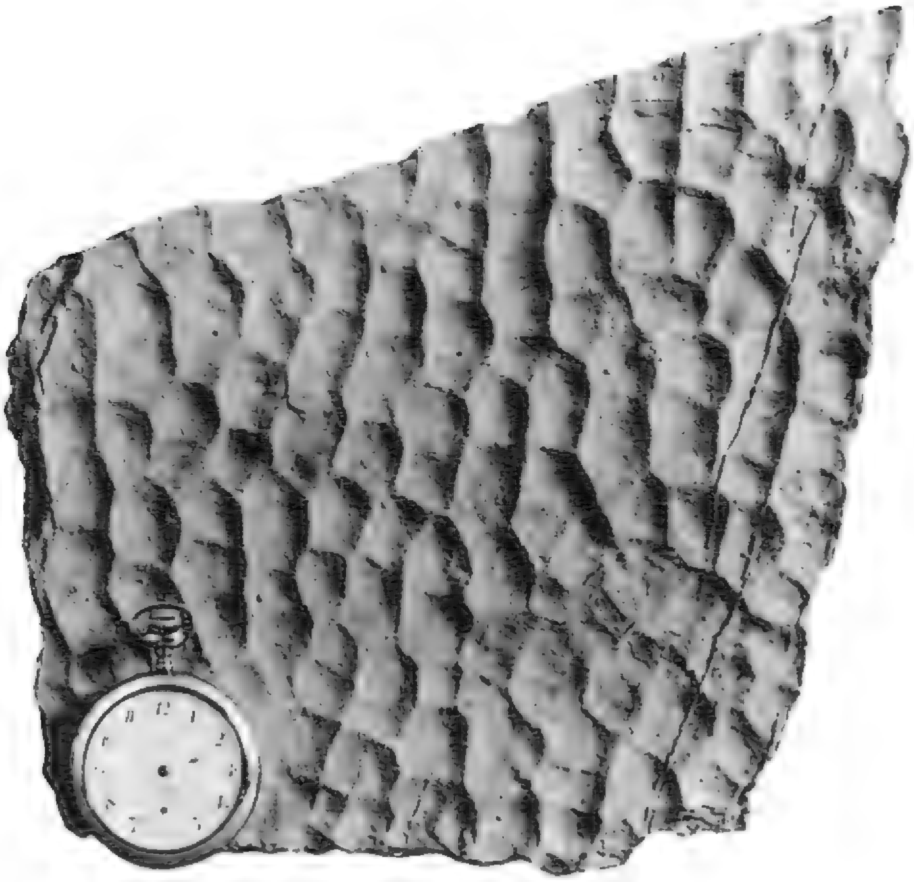
B. Asymmetrical or current ripple-mark on quartzite, Tiger peak, Cour D'Alene district. Photograph by F. L. Ransome, U.S.G.S. (Pages 48, 51.)

A. Asymmetrical ripple-mark, Blacksmith canyon, Logan, Utah. (Page 48.)

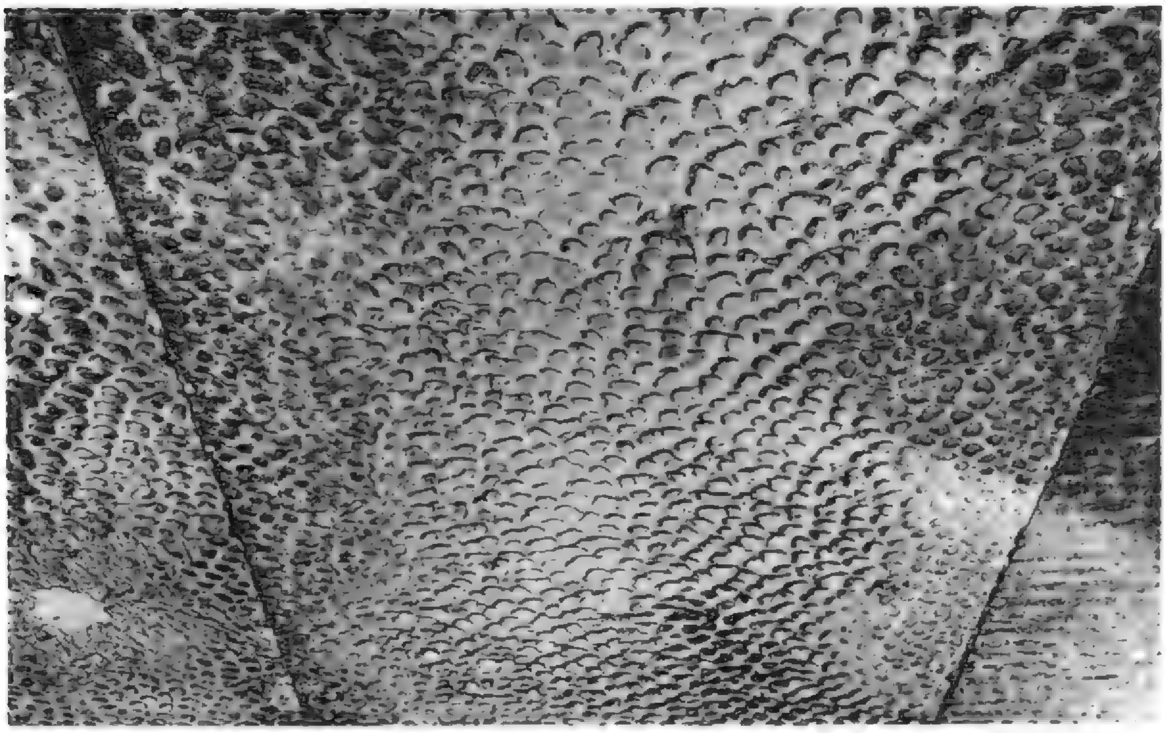


B. Asymmetrical or current ripple-mark with transverse wave ripple-mark on Cambrian sandstone, Castle mountain, B.C. Photograph by L. D. Burling. (Pages 30, 43, 53.)

Asymmetrical ripple-mark crossed by miniature ripple-mark due to waves transverse to the direction of current, Red beds, Muddy creek, Shoshone reservation, U.S.A. Photograph by N. H. Darton, U.S.G.S. (Pages 30, 53.)

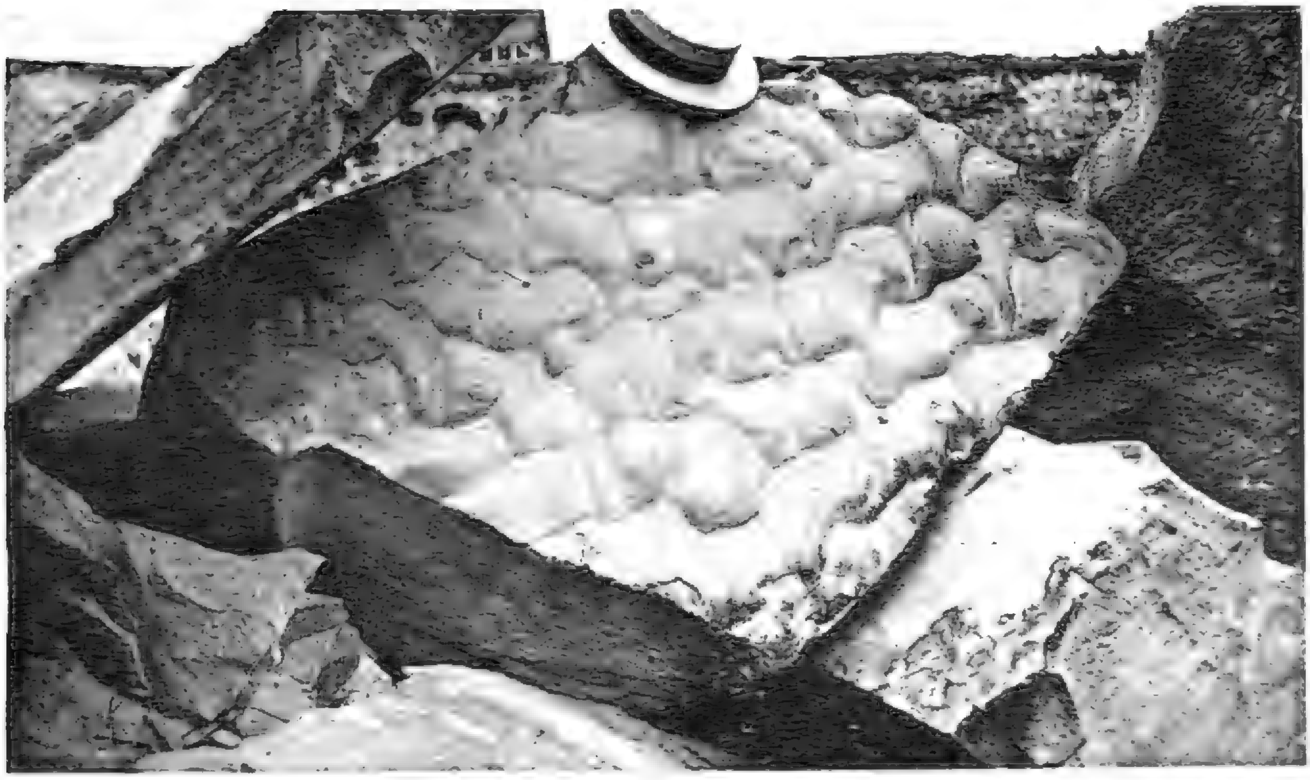


A. Interference ripple-mark on Coal Measure sandstone, Cape Breton, N.S. (Page 43.)

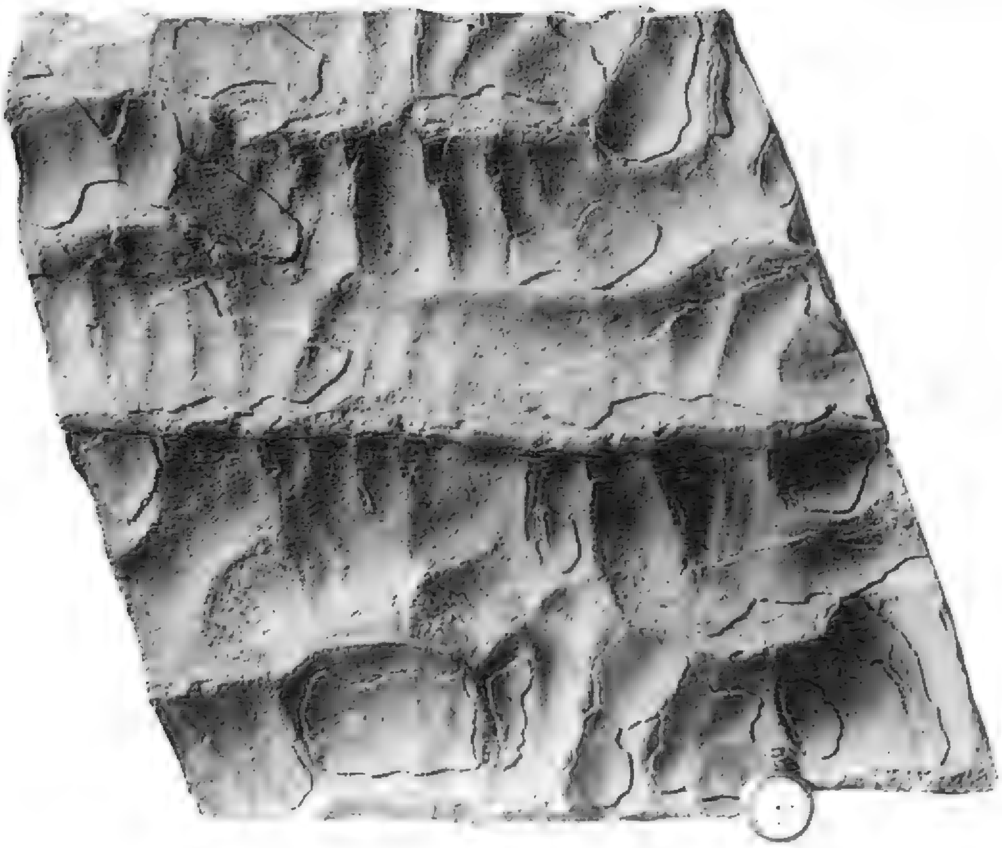


B. Interference ripple-mark on Berea sandstone, Elyria, Ohio. Photograph by G. K. Gilbert, U.S.G.S. (Pages 36, 43.)

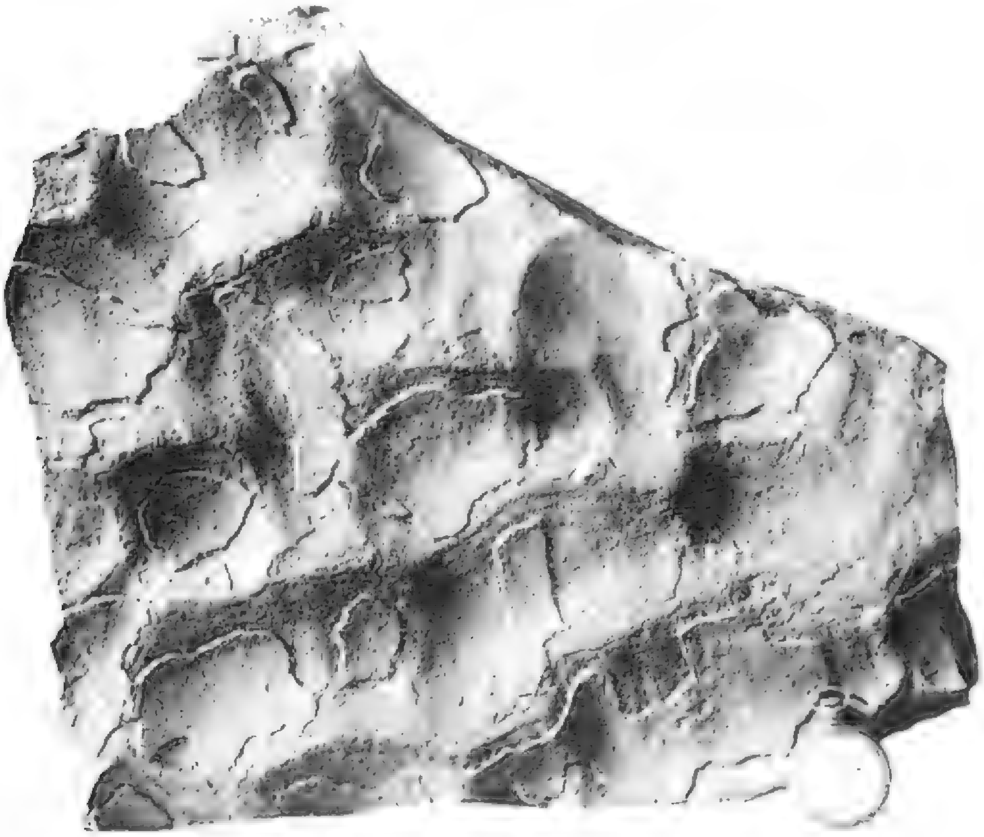
A. Current mark on Carboniferous sandstone, Joggins section, N. S. (Pages 38, 43, 49.)



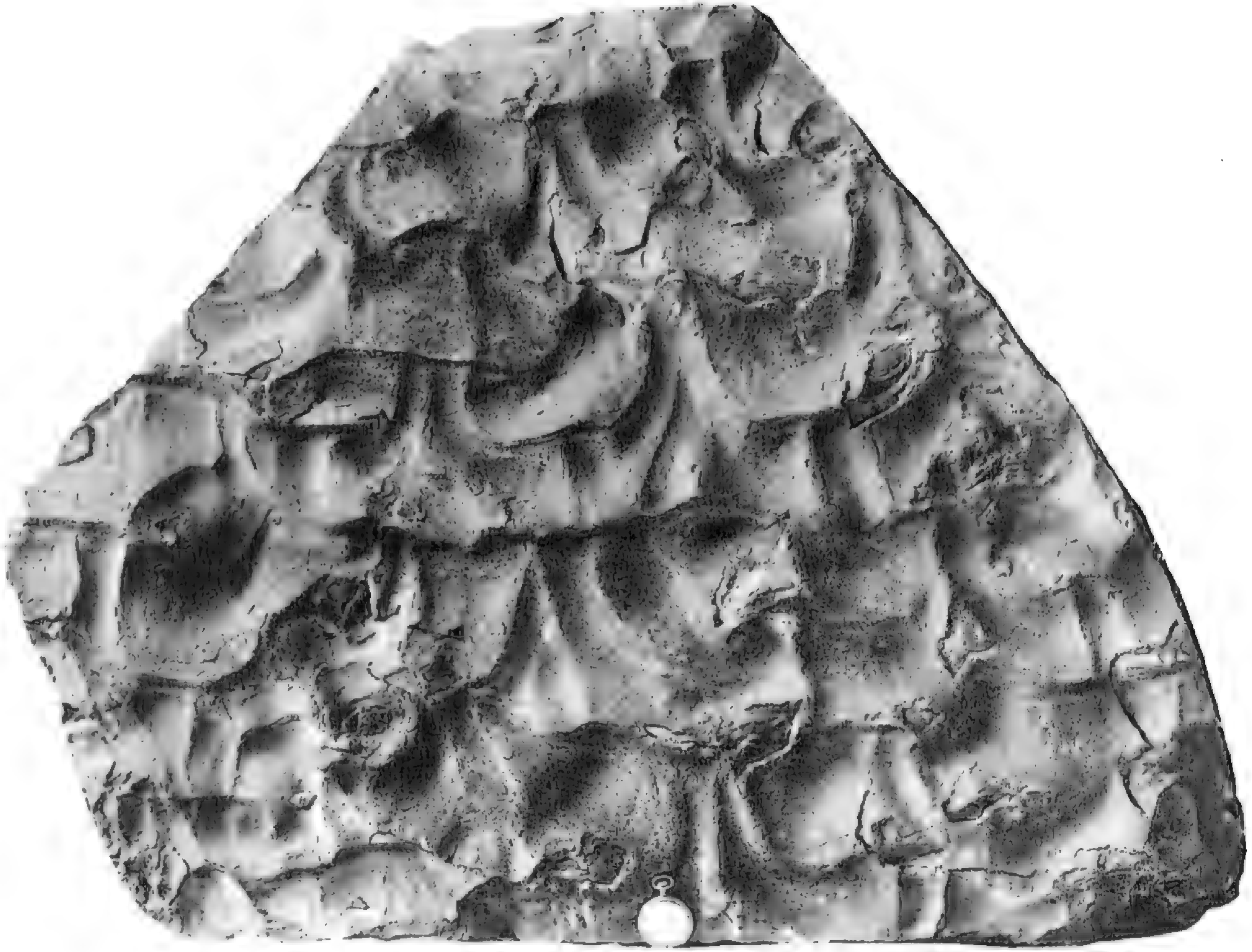
B. Current mark on slab of Carboniferous sandstone, Joggins section, N.S. (Pages 38, 43, 49.)



A. Symmetrical ripple-mark with transverse ripples, on Carboniferous sandstone, Joggins section, N.S. (Pages 43, 49.)



B. Symmetrical ripple-mark with saucer-shaped depressions in the troughs, Carboniferous sandstone, Joggins section, N.S. (Page 49.)



Current mark on Carboniferous sandstone, Joggins section, N.S. (Pages 38, 43, 49.)

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